LDR Segmented Mirror Technology Assessment Study

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Moffett Field, California 94035
Abstract:

In the mid-1990s, NASA plans to orbit a giant telescope, whose aperture may be as great as 30-meters, for infrared and sub-millimeter astronomy. Its primary mirror will be deployed or assembled in orbit from a mosaic of possibly hundreds of mirror segments. Each segment must be shaped to precise curvature tolerances so that diffraction-limited performance will be achieved at 30 μm (nominal operating wavelength). All panels must lie within 1 μm on a theoretical surface described by the optical prescription of the telescope's primary mirror. To attain diffraction-limited performance, the issues of alignment and/or position sensing, position control to micron tolerances, and structural, thermal, and mechanical considerations for stowing, deploying, and erecting the reflector must be resolved. Radius of curvature precision influences panel size, shape, material, and type of construction. Two superior material choices emerged: fused quartz (sufficiently homogeneous with respect to thermal expansivity to permit a thin shell substrate to be drape molded between graphite dies to a precise enough off-axis asphere for optical finishing on the as-received as segments) and a Pyrex or Duran (less expensive than quartz and formable at lower temperatures). The optimal reflector panel size is between 1-1/2 and 2 meters. Making one, two-meter mirror every two weeks requires new approaches to manufacturing off-axis parabolic or aspheric segments (drape molding on precision dies and subsequent finishing on a nonrotationally symmetric dependent machine). Proof-of-concept developmental programs were identified to prove the feasibility of the materials and manufacturing ideas. Such a program would cost between $3M and $5M and could be completed in three to four years.
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INTRODUCTION AND CONCLUSIONS

1.1 INTRODUCTION

In the mid-1990s, NASA is planning to place in orbit a giant telescope, whose aperture may be as great as 30 meters, for infrared and sub-millimeter astronomy. This program, now in an early technical planning stage, is referred to as the LDR (Large Deployable Reflector) Program. This descriptive name derives from its primary mirror, one of the most obvious features of the telescope, which will be deployed or assembled in orbit from a mosaic of possibly hundreds of small mirror segments.

Each of these segments, or panels, must be shaped to precise curvature tolerances so that when they are aligned with respect to each other, diffraction-limited performance will be achieved at the nominal operating wavelength of 30 micrometers. Diffraction limit, in this context, requires that all of the individual panels which comprise the reflecting surface lie within a precision of less than one micrometer on a theoretical surface described by the optical prescription of the telescope's primary mirror. To attain diffraction-limited performance, a variety of technologies must be employed, including alignment and/or position sensing, position control to micron tolerances, and structural, thermal, and mechanical considerations for stowing, deploying, and erecting the reflector.

However, the best sensing and alignment system cannot ensure satisfactory performance if the individual panels themselves do not conform to precise radius of curvature tolerances. A random distribution of radius of curvature errors as small as 100 parts per million could result in wavefront degradation sufficient enough to preclude phased or coherent operation. The ability to produce panels economically and rapidly to these demanding radius of curvature tolerances, to design them in such a manner that this precision is not lost due to temperature or gravity release changes between
manufacture and operation, and to do so without the need for active deformation control, were in fact central considerations for almost every issue associated with panel design. Radius of curvature precision influenced panel size, shape, material, and type of construction.

This report addresses the design requirements and recommended solutions for the development of these panels. It is organized according to the task outline contained in the statement of work, specifically:

1. Development of Requirements and Evaluation Criteria
2. Assessment of Existing Technology
3. Identification and Evaluation of Prime Technologies
4. Analytic Studies and Performance Predictions
5. Design Definition and Concept Selections

During the course of the program, three briefings were presented to the customer. Copies of these briefings are included in their entirety as appendices to this report. The body of the report itself employs key material from these initial, interim, and final briefings plus additional textual material to give the reader sufficient explanatory information to follow the logic leading to the conclusions drawn.

1.2 CONCLUSIONS

The conclusions of this study are summarized in this section.

1.2.1 Materials

Two superior material choices emerged. One was fused quartz, the natural rather than the synthetic product, produced by Heraeus in Hanau, West Germany. This material, Optosil III, appears to be sufficiently homogeneous with respect to thermal expansivity to simply permit the use of a thin shell substrate. We believe, too, that it may be drape molded between graphite dies to an off-axis aspheric shape of sufficient precision for optical finishing to proceed directly on the as-received segments. The need for extensive shaping and material removal is thereby eliminated.
The second choice is Pyrex manufactured by Corning (or Duran, a Schott product). While the homogeneity of this material is not as favorable as quartz, it is less expensive and is formable at lower temperatures. To preclude warping with the large isothermal temperature changes characteristic of the LDR operation, it will be necessary to employ this material in a sandwich configuration such that the effects of through-the-thickness thermal expansion variations are less critical to performance.

1.2.2 Size

We believe that the optimal size for the reflector panels is between 1 1/2 and 2 meters. Larger sizes in the areal density range of interest of 15 to 25kg/m² are either too fragile from a mechanical and producibility aspect, or are too big to confidently expect that the shape of the individual segments could be maintained without the use of bending-type figure control actuators, or both of the above.

1.2.3 Manufacturing Approach

Production rates of a single two-meter mirror every two weeks would be required to make enough panels in seven years for a 25-meter mirror. This is the nature of the producibility issue. To achieve this rate, new approaches to manufacturing off-axis parabolic or aspheric segments are required if an LDR is to become a near-future practical reality. We believe that the approach of producing accurate pre-forms by drape molding on precision dies and subsequent finishing on a CCP* or similar non-rotationally symmetric dependent machine is the best way to produce the reflector panels.

1.2.4 Near-Term Recommendations

A series of proof-of-concept developmental programs was identified to demonstrate the feasibility of the principal ideas contained in the materials and manufacturing areas. This activity would result in the production of several one-meter, 15kg/m² segments embodying the same features and producibility methods that would be used for the full scale 1 1/2 to 2m segments. Such a program would cost between three and five million dollars and could be completed in three to four years.

* The proprietary Perkin-Elmer Computer Controlled Polisher, which will be briefly described later in this report.
SECTION 2

REQUIREMENTS AND EVALUATION CRITERIA

2.1 TOP-LEVEL SYSTEM REQUIREMENTS

A comprehensive set of reflector panel design and performance requirements was derived from the top-level LDR system and programmatic objectives shown in Table 2-1. How they were reduced to requirements for the individual segments or panels will be discussed in Section 2.2.

As shown in Table 2-1, several of these technical and programmatic requirements considerably influenced the areas where emphasis was placed in this study. For example, the overall reflector size range of ±10m about a nominal 20m diameter would have permitted a segment areal density as high as 90kg/m$^2$ for the 10m size but would demand extraordinary efforts to achieve 10kg/m$^2$ in the 30m size range. The former 90kg/m$^2$ unit weight value is not a technical challenge today in 2m sizes, but producing this much glass and finishing all the 27 segments (for a 10m aperture using 2m hexagonal segments) to precise curvature limits in a five to seven year period is. If our efforts were concentrated solely on this producibility issue, however, an LDR would be limited to about ten meters. As such, it would not receive the enthusiastic endorsement of the science community and, therefore, might never happen.

If efforts were concentrated on the 30m size where 10kg/m$^2$ areal densities are needed, the emphasis pendulum would most probably swing over towards novel but highly risky approaches and "gimmicks", again missing the point of a 1987 technology readiness demonstration (another top-level requirement). Therefore, we concentrated our efforts regarding size in the 20m range where the resulting 22kg/m$^2$ areal densities are judged a more reasonable technical challenge and where, of course, the producibility issues still demand solutions. This size is certainly more attractive to the science community and still is sufficiently revealing of 30m technology issues to provide a suitable technological base should this size, and its weight implications, ultimately become the goal.
<table>
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<tr>
<td>Overall Diameter</td>
<td>$10 \leq D \leq 30M$</td>
</tr>
<tr>
<td>Figure Type</td>
<td>Parabola or Hyperbola/Not Simply Spherical</td>
</tr>
<tr>
<td>Figure Quality</td>
<td>D/L $@ \lambda$ = $13.7$ rms or $2.2 \mu$ System $\rightarrow 2 \mu_{rms}$ Mirror</td>
</tr>
<tr>
<td>Speed</td>
<td>$f/0.5$ To $f/1$</td>
</tr>
<tr>
<td>Weight</td>
<td>25000 lbs (11360kg) Including Actuators</td>
</tr>
<tr>
<td>Operating Temp</td>
<td>150 - 200K ($-100$ to $-1900F$)</td>
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<tr>
<td>Operating W/L</td>
<td>2$\mu$ to 1000$\mu$</td>
</tr>
<tr>
<td>Dynamics</td>
<td>0.00035g (Slew), $F &gt; 10$ cps (Spatial Chopping)</td>
</tr>
<tr>
<td>Stability</td>
<td>Passive Segments Preferred</td>
</tr>
<tr>
<td>Technology Demon.</td>
<td>1987</td>
</tr>
<tr>
<td>Operational System</td>
<td>1993</td>
</tr>
<tr>
<td>Deployment</td>
<td>Single STS Flight, Manual Assist OK</td>
</tr>
<tr>
<td>Mission Duration</td>
<td>10 yrs</td>
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Less amenable to compromise or trades than the overall size and areal density issue, and the 987 technology readiness requirements, is diffraction-limited performance at \( \lambda = 30 \) micrometers. This is really the central concept of the LDR — that the entire mirror composed of up to 400 individual segments act optically as a monolithic reflector. As stated in the introduction, new demands are placed on radius of curvature precision, or stated more completely, absolute surface accuracy. Referring back to Table 2-1, there is also a requirement for (light bucket) operation down to wavelengths as short as 2 micrometers. This requirement, in turn, necessitates figure accuracy (relative to a best fit sphere) of between \( \lambda/20 \) and \( \lambda/40 \) rms at 2 micrometers, equivalent to \( \lambda/10 \) in the visible with surface roughness not in excess of 500 Å. A detailed figure error budget will be found in subsection 2.2.1 where traceability back to the top-level performance requirements will be shown.

Thus, at the broadest level, this is the key issue — the rapid production of a large number of lightweight, \( \lambda/10 \) (visible) off-axis parabolas whose radii of curvature are initially matched and thermally stable to a value on the order of 100 ppm over a temperature range of 200°F.

The following discussion addresses in more detail some of the panel design requirements implied by the parameters contained in Table 2-1.

2.1.1 Figure Type

The overall reflector must be parabolic (or aspheric). Unless the primary \( f/No \) was as slow as \( f/100 \), the resultant longitudinal spherical aberration would be in excess of 0.0001 x EFL. For a 10m system, this amounts to 0.01m rms, a useless solution. This is shown graphically in Figure 2-1.

The possibility of approximating a parabola with a large number of small spherical elements was addressed. It was found that individual segments would need to be as small as 0.125m in diameter in order that the differences between radial and tangential sagittas of the prescribed parabola and the local spherical surface not exceed a \( \lambda/40 \) peak-to-peak surface error (ref. error budget). This is illustrated in Table 2-2, based on a 20m diameter, \( f/1 \) reflector. At a point near the rim \( (r = 9.5m) \) the sagittal and tangential radii of curvature are 43.43 and 41.11m, respectively. The mean radius is
Figure 2-1. Longitudinal Spherical Aberration, Spherical Primary Mirror

\[ \Delta S = \frac{R_o}{2} - \frac{r^2}{2R_o} - \frac{r^2}{8R_o^3} - \frac{r}{\tan 2\left[\tan^{-1}\left(\frac{r}{R_o} + \frac{r^3}{2R_o^2}\right)\right]} \]

\[ \Delta s \leq \frac{\lambda}{4} P-P \]

1000 TIMES TOO LARGE FOR 20m SYSTEM!
TABLE 2-2
RADIAL AND TANGENTIAL SAGITTAL DIFFERENCES (ΔSAG)
FOR PANELS IN THE OUTERMOST RINGS

<table>
<thead>
<tr>
<th>DIA (m)</th>
<th>f/No</th>
<th>R (m)</th>
<th>R₁ (m)</th>
<th>SAG₁ (m)</th>
<th>R₂ (m)</th>
<th>SAG₂ (m)</th>
<th>ΔSAG (In)</th>
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<tr>
<td>20</td>
<td>f/1</td>
<td>40</td>
<td>41.11</td>
<td>0.003041</td>
<td>43.43</td>
<td>0.00288</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>(41)</td>
<td>(0.01219)</td>
<td>(43.076)</td>
<td>(0.01161)</td>
</tr>
<tr>
<td>20</td>
<td>f/0.5</td>
<td>20</td>
<td>22.14</td>
<td>0.005646</td>
<td>27.14</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>(21.93)</td>
<td>(0.0228)</td>
<td>(26.37)</td>
<td>(0.01896)</td>
</tr>
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<td>40</td>
<td>f/0.5</td>
<td>40</td>
<td>44.50</td>
<td>0.002809</td>
<td>55.08</td>
<td>0.002269</td>
<td>0.0213</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(44.283)</td>
<td>(0.01129)</td>
<td>(54.27)</td>
<td>(0.00921)</td>
</tr>
</tbody>
</table>

Non-Bracketed Values 1-m Panels
Bracketed Values 2-m Panels
42.27m. The panel center-to-edge curvature depth, or sagitta, is denoted as SAG in the table where the subscripts 1 and 2 refer to the sagittal and tangential directions respectively. The difference between these curve depths relative to the curve depth of the mean spherical radius, $\overline{r}$, is denoted as $\Delta SAG$. The table shows $\Delta SAG$ values for 1- and 2m panels. Only if the panels were as small as 0.125 in diameter would the error budget requirements on $\Delta SAG$ be satisfied (at the edge of the mirror).

The purpose of these investigations was to determine if spherical segments would be optically satisfactory at the wave $= 30$ micrometers operating wavelength, which would greatly simplify the optical figuring process. Rotationally symmetric elements are more easily produced than asymmetric ones and, of course, spheres are symmetric.

But we have concluded that they will not meet performance as practical configuration requirements. So as stated in the introduction, one of the key issues is the efficient production of off-axis parabolic segments. A considerable amount of study effort was directed towards solving this producibility problem.

### 2.1.2 Figure Quality

The implications of diffraction-limited performance on the figure precision of the panels and the requirements imposed by (light-bucket) operation down to wave $= 2$ micrometers will be described in Section 2.2 where error budgets are presented.

### 2.1.3 Weight

Cost is a design dimension for the LDR Program and the goal is to be able to launch and deploy the system with a single shuttle flight, which today costs about $100,000,000. Considering a 64,000 lb total (ETR) lift-off weight to reach the final 400 mile orbit, of which approximately 10,000 lbs is fuel and tankage, some 15,000 lbs is available for the reflector panels. This is illustrated in Figure 2-2.

In this figure, "Spacecraft" refers to that part of the vehicle which includes attitude control, communication, power generation, and the command and control subsystem as well as the structure and crew systems provisions for on-orbit servicing. This weight is on the same order as the spacecraft portion of the Space Telescope (ST). The thermal
enclosure weight is based on the presently envisioned concept of a deployable flexible shroud, stabilized with a "tent pole" framework whose primary functions are to keep sunlight from directly illuminating the reflector, and to provide via controlled radiation paths a cool, uniform, and stable environment for the mirror. We believe that a 200K environment can be achieved with this passive approach.

The Science Instrument weight of 8000 lbs is intended to account for several experiment packages as well as cooling or heat rejection systems necessary for their operation. Those electronics functions which are unique to controlling the reflector, i.e., beyond the scope of the basic spacecraft function, are accounted for in the 2000 lb. weight entry. Thus, we are left with 30,000 lbs for the reflector system. Using the "principle of reasonable proportions", we found that the weight of the integrating structure would be between one-third and one-half of the reflector panel weight for reflectors between 20 and 30 meters. This assumed a 10 cps first mode criteria necessary for pointing control system compatibility.

Each panel will also require at least three actuators for position control. Assuming that 500 panels are necessary to fill the aperture and that each actuator and its associated cabling weighs 5 lbs, 7,500 lbs will be required. This leaves 22,500 lbs for the panels and support structure and, with the 2:1 weight ratio described above in mind, 15,000 lbs are available for the reflector panels. At the 20m size, this represents an areal density of 21kg/m², very light by current standards. At 30m, this value is 9.5kg/m², beyond today's achievements even in moderate size mirrors.

2.1.4 Operating Temperature

The most significant thermal requirement is believed to be the bulk temperature change of -170 to -260°F between fabrication and operation. While axial and radial gradients within a panel can be controlled to acceptably low levels by thermal design techniques, the large isothermal change imposes stringent requirements on material selection, specifically on the homogeneity of thermal expansion (ΔL/L) both within a given segment and between segments. This will be reviewed in considerably more detail in Section 4.
Figure 2-2. Weight Budget (Not Much Available for 20m+ LDRs)
2.1.5 Stability

Once operating temperature is achieved, the thermal environment seen by the segments in benign. It is nominally constant and uniform. In such cases, the need for active figure control, i.e., the compensatory bending of the segments by actuators to nullify the distortions caused by non-uniform temperature distributions, is not mandatory.

It is imperative, though, that the thermal expansion (contraction) of the mirror blank be uniform to a sufficient extent such that the shape of the mirror is preserved over the large bulk temperature change. Allowances for this effect will be seen in the subsequent error budget.

Gravity release deformations also may be considered under the stability topic. The impact of these deformations on the proportioning of the mirror blanks will be covered in Section 3.

2.1.6 1987 Technology Readiness

This system-level objective was interpreted as a design dimension in the following sense. To accomplish the fabrication of several panels and to demonstrate their performance as a flight quality segmented mirror by 1987 virtually demands that materials and processes currently available or nearly so must be employed. This is not to say that optically non-conventional materials cannot be used; in fact, exploitation of such materials and ideas was investigated as a cost or schedule reducer. What was avoided, however, were those expensive approaches which are still only laboratory curiosities, where scale-up to the panel sizes required or quantities necessary would entail major capital expenses or uncalculable technical risk.

2.2 PANEL DESIGN REQUIREMENTS

These top- or systems-level issues were reduced to specific design requirements at the individual reflector panel level. We believe that the most important technical requirement to have come out of this investigation is radius of curvature precision. It affects panel size, shape, material selection, structural configuration, and optical producibility. In short, it is the driver in coherent segmented mirror design.
Figure 2-3. Figure Control Definitions (Schematic)
As stated earlier, it is desirable to avoid the use of two levels of figure control, as illustrated in Figure 2-3. While it is necessary in certain programs where the thermal environment is significantly transient and non-uniform to series-combine bending and position figure control, we believe the more economical approach, considering the relatively stable environment surrounding the mirror, is to employ dimensionally stable panels and position control only. This, as will be shown later, favors smaller segments and, hence, more "Level 1" or position control actuators. But on the whole, fewer actuators per square meter, simpler on-board electronics and sensing, lower weight, and reduced cost are anticipated.

2.2.1 Panel Error Budget

Figure 2-4 shows the error budget from which the panel performance and manufacturing requirements were derived. It presumes a two-mirror telescope whose static, jitter-free performance at the second focus is \( \text{wave/13.7} \), a commonly accepted definition for diffraction-limited wavefront quality. Except for the \( \Delta R \) terms, it is similar in content to error budgets for systems with monolithic, or one-piece, primary mirrors. In such systems, if the radius of curvature of the primary is somewhat different from the nominal design value, a slight adjustment of the spacing with respect to the secondary can compensate for it, albeit with refocussing at the final image. With a segmented mirror, each panel of which might/will have a radius of curvature error, this obviously cannot be accomplished. In this instance, radius of curvature errors are analogous to mid-frequency figure errors in a monolith.

An expression relating radius of curvature error to wavefront error was derived to quantify how well each panel had to conform to its prescribed radius. This expression is based on a Gaussian, or random, distribution of curvature errors, which is deemed valid for a system composed of a large number of panels. It would not be entirely valid if only a few, say three or five, panels were employed and could be treated systematically:

\[
\Delta WF = \frac{1}{3.46} \left( \frac{r}{R} \right)^2 \Delta R \text{ rms}.
\]

In this expression, \( R \) is the nominal radius of curvature and \( r \) is the half span of an individual panel, as shown in Figure 2-5.
DIFFRACTION LIMITED PERFORMANCE AT 30 μm = \frac{30}{13.7} = 2.2 μ rms

STATIC SYSTEM WAVEFRONT
ΔWF = 2.2 μ rms

SECONDARY MIRROR
ΔWF = 0.5 μ rms

PRIMARY MIRROR
ΔWF = 2.1 μ rms

PRIMARY/SECONDARY ALIGNMENT
ΔWF = 0.5 μ rms

ALIGNMENT SENSING AND CONTROL
ΔWF = 1.2 μ rms

REFLECTOR PANELS
ΔWF = 1.7 μ rms

FABRICATION
ΔWF = 1.2 μ rms

DESIGN RESIDUAL
ΔS = 0.66 μ rms

MANUFACTURING
ΔR = 1 μ rms

MECHANICAL
ΔS = 0.66 μ rms

THERMAL
ΔT = 1 μ rms

INTENTIONAL FIG. DEVIATIONS
ΔS

EXTERNAL EDGE EFFECT
ΔS

GAP EFFECTS
ΔS

METROLOGY
ΔR

MATERIAL REMOVAL
ΔS

METROL. MT
ΔS

GRAV. RELEASE
ΔR

RESIDUAL LAUNCH STRAINS
ΔR

MOUNT CONSTRAINTS
ΔR

TEMPORAL EFFECTS
ΔR

COATING AND BI-METALLICS
ΔR

LUSTR.
ΔR

Axial Grad
ΔR

Lateral
ΔR

NOTES:
1. ΔS = WAVEFRONT ERROR DUE TO FIGURE CHANGE (rms)
   ΔR = WAVEFRONT ERROR DUE TO RADIUS CHANGE (rms)

2. TOTAL RSS ΔR WAVEFRONT ERROR = .95 μ rms

   MFG RSS ΔR WAVEFRONT ERROR = .5

   OP'N RSS ΔR WAVEFRONT ERROR = .81

Figure 2-4. Wavefront Error Budget
Figure 2-5. Radius of Curvature Precision — A Big Driver for Phased (Coherent) Operation

\[ \Delta WF = 1/3 \left( \frac{r}{R} \right)^2 \Delta R \quad \text{AND} \quad \Delta R = \frac{R^2 \alpha \Delta T}{h} \]

\[ \Delta WF = 1/3 \; r^2 \alpha \frac{\Delta T}{h} \]

FAVORS SMALL PANELS
For the case of a simple axial temperature gradient ($\Delta T'$) or a bulk average temperature change ($\Delta T$) acting on panels with axial expansivity inhomogenities,

$$\Delta R = \frac{R^2 \Delta T'}{h}, \quad \frac{R^2 \alpha \Delta T}{h}$$

where $h$ is the panel thickness. Substituting this into the WF expression, one finds that

$$WF = \frac{1}{3.46} \frac{r^2 \Delta T'}{h}, \quad \frac{1}{3.46} \frac{r^2 \alpha \Delta T}{h}$$

for axial gradient and bulk average temperature changes, respectively. This suggests the advantage of "small" panels from a thermal or material homogeneity aspect.

The manufacturing precision, which may be expressed as $\Delta R/R$, is obtained by rearranging the first equation and is equal to

$$\frac{\Delta R}{R} = \left( \frac{3.46 \frac{R}{r^2}}{r^2} \right) \Delta W F_{rms}.$$

Figure 2-6 shows graphically the relationship between $\Delta R/R$, segment diameter, and nominal radius of curvature for the 0.5 micrometer, or wave/60, wavefront error allocation shown in Figure 2-4. In terms of absolute surface contour error, from the familiar $\Delta = \frac{r^2}{2R}$ equation for the sagitta of a parabola, there is no size-dependent effect. Manipulation of the above equations shows that

$$\Delta \sim 1.7 \; WF_{rms}.$$

However, the issue when $\Delta WF = 0.5$ micrometer rms is the relative difficulty between fabrication of a 60-inch-diameter optic to an absolute surface precision of 0.35 micrometer, or $30 \times 10^{-6}$ inches rms, versus an 80" or larger optic to the same tolerance. It is generally agreed that such a trade would favor the smaller sizes.

Turning our attention to the thermal issue, we can illustrate further the small panel advantage. Consider for simplicity a panel configured as a shallow solid shell. It is
\[ \frac{\Delta R}{R} = \left( \frac{3 \Delta \Phi}{f^2} \right) \Delta W F_{rms} \]

**Example shown for f/1**

Double \( \Delta R/R \) values for f/2, etc.

\( \phi = 20 \text{ m}, \ R = 40 \text{ m} \)

\( \phi = 25 \text{ m}, \ R = 50 \text{ m} \)

\( \phi = 15 \text{ m}, \ R = 30 \text{ m} \)

Figure 2-6. Required Radius of Curvature Precision for Wave/60 rms Coherence WF Error
presumed are all materials will exhibit some degree of coefficient of thermal expansion (CTE) inhomogeneity. And, in fact, this inhomogeneity will vary not only within a given part but also from part-to-part due to process and/or batch variations. Considering only the part-to-part variances, the maximum allowable difference in the CTE axial homogeneity between panels is given by

\[ \Delta \alpha' \leq \frac{3.46 \Delta W_F \text{rms} h}{r^2 \Delta T} \]

The terms in this equation are defined in Figure 2-7 where \( \alpha' \) is axial inhomogeneity and \( \Delta T \) is the bulk average temperature change of the panel, approximately -170°F between factory and orbit. To relate overall reflector diameter to glass thickness "h", a constant reflector weight of 15,000 lbs was assumed. Once again, a greater than 2:1 advantage was found between 2 and 1.3m panels. At 4m, this ratio would have been 9:1.

It should be noted that regarding a 1.3m panel for a 20m reflector, a \( 4 \times 10^{-10} \) inhomogeneity value is approximately equal to one part in 750 for fused quartz and one part in 75 for Zerodur (\( \varepsilon = 0.3 \) and 0.03 x \( 10^{-6} \) in/in/°F respectively) and that data is available indicating that these values can be met.

While the \( \Delta \alpha' \) parameter was illustrated for solid mirrors, it is also applicable to sandwich mirrors where it defines the CTE mismatch limits between the front and back plates. For example, if "h" in this instance is 4 inches and \( \Delta T \) is 170°F, the front-to-back matching for a 2m panel such that the wavefront error did not exceed 0.5m would be \( 13 \times 10^{-10} \), or 7 times that of the reference solid. Trades between thin shell solid mirrors and sandwich configurations will be reviewed in a subsequent section.

2.2.2 Packing Efficiency

Another size consideration is packing efficiency relative to the cargo bay diameter. For hexagonal panels, one 4m, one 3-2.5m, and one 7-1.7m panel could all be placed in a single plane whose superscribed diameter is 4.5m. For trapezoidal (square) panels arranged in a square array, as shown in Figure 2-8, this selection is one at 4.5m, four at 2.25m, and none at 1.5m (measured on the diagonal). The packing efficiency is shown in Table 2-3.
Figure 2-7. Glass Homogeneity Requirements -- Thermal/Operational
Figure 2-8. Preassembled Panel Module Concept
TABLE 2-3
PACKING EFFICIENCY

<table>
<thead>
<tr>
<th>Major Dimension</th>
<th>Number</th>
<th></th>
<th>Area (m²)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Hexagonal</td>
<td>Square</td>
<td>Hexagonal</td>
</tr>
<tr>
<td>4m</td>
<td>1</td>
<td>1</td>
<td>12</td>
</tr>
<tr>
<td>2.5m</td>
<td>3</td>
<td>4</td>
<td>14</td>
</tr>
<tr>
<td>2.25m</td>
<td>4</td>
<td>4</td>
<td>10.1</td>
</tr>
<tr>
<td>1.7m</td>
<td>7</td>
<td>9</td>
<td>11.8</td>
</tr>
<tr>
<td>1.5m</td>
<td>7</td>
<td>9</td>
<td></td>
</tr>
</tbody>
</table>

This table shows the packing efficiency of hexes with respect to squares and the minor advantage of small hexes as opposed to large ones. Practically, however, the hex vs. square advantage will be diminished when consideration of support cradles to hold the panel module during ascent is factored in. This is indicated by the 7-1.5m hex module whose packing efficiency is only 17% greater than the square. It should also be noted that an array of squares (or more precisely trapezoids) can better approximate a circle than an array of hexes, which is an optical performance advantage.

2.3 EVALUATION CRITERIA

At this point, we have established that the panels need to be:

- lightweight (10-20 kg/m²)
- between 1 1/2 and 2 meters in size (hexes or trapezoids are acceptable)
- off-axis parabolas with base radii precise to about 100 ppm
- thermally stable and homogeneous to preserve this curvature accuracy as well as the figure accuracy of wave/40 p-p necessary for light-bucket operation
- producible economically in large quantities at rapid rates.
There are potentially many material and configuration choices and combinations that might be able to meet the above requirements. Some are more suitable from a system compatibility aspect than others. To address this issue as well as the producibility question, we assembled a list of evaluation criteria to serve as guides in narrowing down the number of solution possibilities. These criteria are most succinctly found in Appendix A, First Briefing and in Appendix B, LDR Interim Review. They covered a wide spectrum of considerations spanning the issues of shuttle bay stowage, erectability, and alignment sensing system compatibility (all related to segment size which, in turn, is influenced by material selection, structural form, and dynamic and thermal characteristics) to the more immediate concerns of producibility, an issue which encompasses segment size, material and facilities availability, materials utilization, experience and usage history, and the rapid production of off-axis aspherics.

Attempts were made (see Appendix B) to systematically relate the four principal segment questions — size, shape, material, and structural configuration — to the general evaluation categories of performance capability, overall system and mission compatibility, cost and schedule projections, and risk or degree of development required. What we concluded from these sorting exercises was that glass or glassy-ceramic materials were required based on performance, that panel sizes in the 1 1/2 and 1/2- to 2m sizes were optimally driven by the goal of passive stability as well as structural and dynamic considerations consistent with the 15-20 kg/m² areal density constraint, and that all of these factors considered together caused producibility to emerge as the governing concern.

How these issues all relate is seen in Figure 2-9. This figure traces the way the requirement for absolute figure precision, or $\Delta R/R$, drove the materials selection which, in combination with the weight/areal density requirement, had profound influence on how the mirror blanks would need to be fabricated and optically finished. What this figure shows is the sharp break-point in material homogeneity requirements between 2- and 4m panels which is based on the relationship shown in Figure 2-7. Referring to Figure 2-10, panel sizes on the order of 1m are deemed impractically small from the aspect of the sheer number required and the number of position actuators (and cabling) which is (at least) three times the number of panels.
\( \Delta R/R \)

CTE AXIAL HOMOGENEITY DIFFICULTY INDEX

<table>
<thead>
<tr>
<th>1-m</th>
<th>1.5-m</th>
<th>2-m</th>
<th>...</th>
<th>4-m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.1</td>
<td>16</td>
<td>...</td>
<td>251.8</td>
</tr>
</tbody>
</table>

TRADEABLE WITH:
- ACTUATORS/m²
- EDGE EFFECTS
- SENSING AND CONTROL IMPLEMENTATION DEPLOYMENT

1.5-2 m PANELS

UP TO 800 REQUIRED FOR A 30-m LDR

OPTICS MANUFACTURING
- \( \Delta R/R \) INITIAL PRECISION
- OFF-AXIS ASPHERICS
- TIME

REPLICATE ACCURATE PREFORMS

WEIGHT REQUIREMENTS
- 15 kg/m² TERRITORY
- EQUIVALENT TO 1/4" SOLID GLASS
- FRAGILE MIRRORS
- AVOID MACHINING LOADS

SHAPE
- HEX VS TRAPEZOID

TRAPEZOIDS HAVE A TOOLING ADVANTAGE

SOLID VS. SANDWICH VS MATERIAL AND PROCESSES

COST

REPLICABLE
INVENTION REQUIRED
- AND WE DID!! -

HIP COILZAK CORNING PYREX QUARTZ ZDUR
BERY. ALUM TGC

Figure 2-9. The \( \Delta R/R \) Influence Tree
Figure 2-10. Number of Segments and Number of Different Segment Types to Fill an Aperture (Δ = Number of Different Figure Types)

n = \frac{25}{1000}

1.35 m TRAP.
1.5 m HX.
2 m TRAP.
2 m HX.
4 m TRAP.
4 m HX.
In addition, for a given areal density, frequency is inversely proportional to the diameter squared, making $4=\pi d$ mirrors impractical. It is shown later in Section 4 that the first mode of a 2m, $17\text{kg/m}^2$ (thin shell) mirror with a major diameter $d$ is 11 cps. At the same areal density, this would be reduced to three cps for a 4m mirror. This is too low considering the ten cps disturbance frequency associated with the background chopping mode. Further, only one facility exists capable of producing ultralightweight glass mirrors as large as 4m with areal densities in the $20\text{kg/m}^2$ ($0.3''$ equivalent solid thickness) range. That is the Schott Co. in Mainz, W. Germany and the material is Zerodur. The $1g$ handling stresses would exceed 5000 psi which, referring back to the evaluation criteria contained the the appendices, fails in the fragility category for a thin shell mirror.

In a word, 1m panels are too small from a controls aspect and 4m panels are too large from a structural, dynamic, availability, and risk aspect. Hence, the 2m to 1.35m size is the most viable. Note that these sizes are evenly divisible into the basic 4m diametrical space available within the orbiter bay. The 0.5m margin between the 4m panel module size and the 4.5m bay diameter was reserved for support structures and deployment devices. Note, too, that the use of the word "module" signifies that four or nine (trapezoidal) 2- or 1.35m panels could be preassembled on the ground and stowed in the orbiter as a unit, as shown in Figure 2-9.

Implicit in the above discussion is the desire to employ thin shell mirrors. Such mirrors, although critically dependent on the spatial uniformity of the thermal expansivity, are most compatible with the idea of semi-replication on the forming of the shell to the approximate off-axis parabolic shape. They avoid the high material removal rates associated with conventional optical operations. A method has been identified whereby the semi-replication, or accurate preform approach, can be applied to sandwich or structured mirrors as well. A sandwich mirror relieves, by an order of magnitude, the degree of homogeneity needed for the thin solids. (Refer to the equation in Figure 2-7 where "$h$" for the sandwich might be 3" or 0.3" for a solid.)

The issues of quantity and manufacturing interact and together are influenced by weight, or more specifically the fragility associated with very-low-areal-density, moderately large mirrors. As seen in Figure 2-9, these considerations led to the idea of replication or at least the production of accurate preforms which would minimize the
time required to optically finish the parts and reduce the risk of damage associated with high material removal rates on very lightweight substrates.

This, in turn, led to a search for materials which were compatible, at least in principal, with the production of accurate preforms and which also met the requirements for figure stability (homogeneity) between room and operating temperature ($\Delta T \approx 200^\circ F$). Associated with this materials evaluation task are the evaluation criteria:

a) **Does the material exist today and is it producible in the size range of interest?** The thrust behind this question is to avoid dependence on materials which are limited by process physics to small sizes or unsuitable forms where scale-up to the size range of interest could be a program stopping risk.

b) **Does the material exist today and is it optically of interest?** New materials, particularly ceramics and glassy ceramics and composites, are rapidly emerging as engineering realities. Some of them possess many attractive features for mirror substrates but might fall short in one or several critical areas. Surface granularity in some ceramics and CTE content in composites are two examples of such concerns. The continued development effort to rectify these problems is often a very lengthy, somewhat invention-dependent process. We therefore believe the better approach is to exploit existing, proven materials and to place the engineering emphasis on methods for lightweighting and related configuration issues.
SECTION 3

CURRENT TECHNOLOGY ASSESSMENT

The requirements developed in the previous section are summarized in Table 3-1 for a variety of overall mirror diameters, f/No's, and segment sizes. Note that because the thickness of a solid segment applicable to a 25m LDR can only be 6.4mm (0.25 inches) based on weight considerations, the panel-to-panel variation in the coefficient of thermal expansion in the thickness direction is limited to $1 \times 10^{-10}/\text{OF}$. This may be too stringent a requirement to expect of even the best materials. On a unit basis, this is equal to $4 \times 10^{-10}$ in/in/°F per inch of thickness. If, then, the mirror were a 4-inch-thick sandwich, and the back and front faceplates were matched to $16 \times 10^{-10}$, then the response to a bulk average temperature change would be the same as that of a 6.4mm thin shell whose expansivity difference is $1 \times 10^{-10}$.

With this last factor in mind, the focus of the "current technology assessment" task was concentrated in three areas:

1. Production of off-axis aspherics.
2. Materials which were compatible with semi-replication and which were highly homogeneous and suitable for solid mirrors.
3. Techniques for rapidly producing semi-replicated sandwich mirrors.

3.1 PRODUCTION OF OFF-AXIS ASPHERICS

Optical design requirements demand that the overall reflector be parabolic. This in turn requires that each panel must be an off-axis aspheric. Because of differences in radial and tangential curvatures of these elements, it is not possible to adequately simulate the parabolic shape with spherical elements.

The consequence of this is principally a manufacturing issue. Rough shaping of mirror blanks, using spherical generating techniques, depends on the property of circular symmetry. The majority of the fine shaping, or figuring, processes employed in the
# TABLE 3-1.
LDR REQUIREMENTS SUMMARY

<table>
<thead>
<tr>
<th>Figure Type</th>
<th>OFF-AXIS PARABOLIC SEGMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.0m</td>
</tr>
<tr>
<td></td>
<td>1/0.5</td>
</tr>
<tr>
<td>Nominal Radius of Curvature</td>
<td></td>
</tr>
<tr>
<td>Number Panels Required</td>
<td>HX</td>
</tr>
<tr>
<td>TRPZ</td>
<td>250</td>
</tr>
<tr>
<td>Number Different Panels Required</td>
<td>HX</td>
</tr>
<tr>
<td>TRPZ</td>
<td>7</td>
</tr>
<tr>
<td>Radius of Curvature Precision, mm</td>
<td>0.69</td>
</tr>
<tr>
<td>(δR = 3.46δR^2/r^2, δW1rms, and δWФ = 0.3μm)</td>
<td></td>
</tr>
<tr>
<td>Corresponding Sagitta Error, mm</td>
<td>0.00057 (32 μinches)</td>
</tr>
<tr>
<td>Figure Error Allowable</td>
<td></td>
</tr>
<tr>
<td>Areal Density, kg/m²</td>
<td>1/8 rms @ 1+2 μm</td>
</tr>
<tr>
<td>HX</td>
<td>39</td>
</tr>
<tr>
<td>TRPZ</td>
<td>18</td>
</tr>
<tr>
<td>Solid Thickness (b), mm</td>
<td>5.2</td>
</tr>
<tr>
<td>δb ≤ 10-10</td>
<td></td>
</tr>
<tr>
<td>(δb = 3.46δW1rms/QF and δWФ = 0.3μm, δt &gt; 170°F)</td>
<td></td>
</tr>
<tr>
<td>δb ≤ Applicability</td>
<td></td>
</tr>
<tr>
<td>(S = Solid, C = Cored Sandwich)</td>
<td>S, C</td>
</tr>
</tbody>
</table>

* * *
optics industry today to modify the spherical blank into a parabola, or other desired asphere, also rely on this property. It will be shown later that this is not universally true; advanced machines such as the Perkin-Elmer Computer Controlled Polisher (CCP) can produce virtually any shape. This machine, however, is most effectively employed only after the blank is rough shaped to within several micrometers rms of its desired final figure.

Because the off-axis elements have significant departures from a best-fit sphere, conventional spherical generating techniques are inadequate. Using a 20m, f/1 parabola as an example, the instantaneous radii of curvature in the radial and tangential directions at a distance of 0.75m from the edge are 41.11 and 43.43 meters respectively. Assuming a 1.5m panel size, the depths of curvature, or sagitta, in these two directions are 0.00684 and 0.006648 meters. The difference is 360 micrometers or 0.0144 inches, a considerable amount of material to be removed from a figuring aspect using the CCP machine.

Methods are under development, notably by Dr. Jerry Nelson at Berkeley, to pre-bend mirror blanks in a specific way, generate them as spheres, and then release the constraints and allow the piece to relax into the desired (off-axis) parabolic shape. Such techniques are not so readily employed with the extremely lightweight sandwich structures envisioned for the LDR Program due to fragility, quilting potential, and structural orthotropy, the last being a property of square grid sandwich mirrors. However, the CCP machine can also perform rough grinding operations unconstrained by rotational symmetry. But because of the small tool sizes employed by this machine, the process is less rapid than with the classical approach.

A potential solution for overcoming this slowness lies with semi-replication, or accurate "preforms", such that the basic aspheric shape of the mirror is "molded in" though not necessarily to optical quality tolerances, reducing the amount of material that needs to be removed. If this can be achieved, then all optical operations could be performed on the CCP machines more quickly and economically. Concepts for preforming mirror blanks will be described later in this report for both thin solid and sandwich configurations.
Figure 3-1. Perkin-Elmer Computer Controlled Polisher (CCP) Operation Cycle
The CCP machine system is illustrated schematically in Figure 3-1. The grinding head is carried by an X-Y carriage assembly and may be programmed to follow spiral, raster, or any other desired path while the tool itself rotates at a constant velocity. By varying the dwell rate \((x, y)\) at any \(x-y\) position, the amount of material removed at that position may be controlled. Constant tool pressure is maintained by a pneumatic spring. A single complete process loop is shown in this figure where:

a. The surface error to be corrected is determined by, full aperture interferometry. Profilometer measurements could also be employed if the surface is so far from an optically good surface that interferometric methods would be impossibly difficult to interpret.

b. A percentage of the total amount of material to be removed is selected and, based on tool mechanics, dwell times over the piece are determined. The times are then converted into an X-Y displacement schedule. These operations are carried out within the machines' dedicated computer.

c. The actual grinding or polishing operation is carried out. This may encompass several identical passes over the mirror surface.

d. The figure is finally remeasured to verify that what was commanded to be removed actually was, and to determine the next removal schedule.

This process might be repeated between five and fifteen times to achieve the desired final figure perfection. As stated earlier, on-axis or off-axis does not matter. The \(X, Y\) program is in no way symmetry-dependent.

As it concerns LDRs, the CCP exerts very low forces on the mirror panels, a necessary element considering how lightweight they are. The tools are small, which is important in avoiding quilting in sandwich applications with thin faceplate. The more critical issues are probably measuring off-axis elements and the ability of the machine to "clean up" the as-received surface (which will most likely contain high spatial frequency errors from the molding (replication) process and may demand extreme agility of the \(X, Y\) program). The measuring of off-axis elements interferometrically presents problems since the optical axis or vertex of the element does not physically exist and centering of the mirror and null lens becomes difficult, if not imprecise. We will subsequently describe a measuring system that does not rely on interferometry as a potential solution.
to this problem and which solves the problem of how to measure an as-received surface, one whose surface is (probably) too diffuse or irregular to permit interferometric techniques to be used.

3.2 MATERIAL SELECTION

Initially it was hoped that a sufficiently homogeneous material could be found with a low enough softening, or forming, temperature to permit molding or replicating of the off-axes panels. Ideally, the optical shop would only need to "shine" the surface to about 1000 Å to make it sufficiently specular at wave = 30 micrometers. Such a process would tend to ensure that each panel in a given radial position would have identical curvatures, an effective way to solve the ΔR/R manufacturing issue. It would also minimize to almost zero the amount of material that would have to be removed by controlled grinding, a classically time consuming process. Short of reaching this goal, accurate preforms, not quite to final curvature tolerances, would still represent a major time savings.

Table 3-2 summarizes the pertinent characteristics of the six leading candidate LDR materials, the latter two of which are metals. Composites such as graphite-epoxy were also considered but were rejected for reasons discussed at the end of this paragraph. The important homogeneity parameters ΔA and Δd refer to the average CTE difference between mirrors and the difference between through-the-thickness, mirror-to-mirror CTE variations respectively. The former is important in sandwich applications where front plate and back plate CTE differences from mirror to mirror will cause a ΔR error distribution to occur when the average temperature is changed. Of the materials investigated, Heraeus Fused Quartz and Schott Zerodur appear to possess the necessary homogeneity requirements for thin shell applications. However, the accuracy of the molding process with both of these materials will require approximately 10 mils of material removal. We might thus expect reasonably accurate preforms and not "shine-only" replicas. Heraeus Fused Quartz is moldable, as shown in Table 3-2, at approximately 1800°C in an oxygen-free atmosphere using graphite dies. Schott Zerodur is moldable at much lower temperatures (800°C), but in glassy or non-ceramed state. Subsequent ceraming to reduce the expansivity from nominally 2 ppm/°C to the range of interest required will result in distortion. It is the extremely high quartz
### TABLE 3-2
CANDIDATE MATERIALS AND PRODUCIBILITY FACTORS

<table>
<thead>
<tr>
<th>Candidate Materials</th>
<th>Δα Solid</th>
<th>Δα Sandwich</th>
<th>Δα Solid</th>
<th>Δα Sandwich</th>
<th>Forming Temp</th>
<th>Frits, Adhesives</th>
<th>Delivery Rate</th>
<th>Current Size Limit</th>
<th>Cost</th>
<th>2μ Perf</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heraeus Fused Quartz</td>
<td>-</td>
<td>J</td>
<td>J</td>
<td>-</td>
<td>200°C</td>
<td>NO</td>
<td>SLOW</td>
<td>45°</td>
<td>HIGH</td>
<td>YES</td>
</tr>
<tr>
<td>Schott Zerodur</td>
<td>-</td>
<td>J</td>
<td>J</td>
<td>-</td>
<td>800°C*</td>
<td>YES</td>
<td>FAST</td>
<td>250&quot;</td>
<td>HIGH</td>
<td>YES</td>
</tr>
<tr>
<td>Corning Pyrex</td>
<td>-</td>
<td>(                )</td>
<td>J</td>
<td>-</td>
<td>~</td>
<td>YES</td>
<td>(FAST)</td>
<td>?</td>
<td>LOW</td>
<td>?</td>
</tr>
<tr>
<td>HIP Beryllium</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>?</td>
<td>800°C</td>
<td>NO</td>
<td>(FAST)</td>
<td>48&quot;</td>
<td>MODERATE/HIGH</td>
<td>YES</td>
</tr>
<tr>
<td>&quot;Coilzak&quot;/AL.Foam</td>
<td>-</td>
<td>(J)</td>
<td>N/A</td>
<td>RT</td>
<td>YES</td>
<td>FAST</td>
<td>80&quot;</td>
<td>VERY LOW</td>
<td>NO</td>
<td></td>
</tr>
</tbody>
</table>

*Subs. Ceraming Required
molding temperature and the subsequent Zerodur heat treating operation that fundamentally limit the accuracy of these preforms. No other materials appeared to be sufficiently homogeneous for thin shell applications.

We found that Corning Pyrex and probably Schott Duran, much cheaper materials, would be adequately stable in sandwich configurations. They might result in a more economical approach despite the fact that a core structure and back plate would be required and that an appropriate fit for these materials — and the attendant application and firing facilities — would have to be developed.

Figure 3-2 illustrates how CTE bounds were arrived at for the LDR panels. This figure plots CTE against the allowable back-to-front temperature difference for a variety of mirror thicknesses for the specific wavefront error allocation shown in Section 2. These results are for 1m panels and would be reduced by the square of the diameter for larger panels as indicated by the $\Delta T$ equation in the figure. The figure also shows the predicted axial temperature differences that would exist in typical LDR ultralight-weight sandwiches due to the thermal resistance of the core structure. Indicated along the bottom are the CTE values of the candidate materials at 200K. Pyrex is just acceptable although reallocation of tolerances and a larger allowable $\Delta WF$ error, always a possibility in the trade stages of a system's development, might provide a more comfortable margin for this potentially attractive material.

The $\Delta T_C$ values for all glass and glass-ceramic solids and metals are less than the cutoff lines shown on the curve and, hence, these materials are all viable, up until subsequent limiting criteria are discussed. The "XXX" material is a non-designated lithium silicate which Corning suggested as a potential LDR material. It was originally developed in the 1940s as a lower expansion replacement for Pyrex for mirror applications but is not currently in production.

Metals, aluminum honeycomb, or foam core sandwiches, for example, were "in the running" for a long period of time. The stamped, or replicated, Alcoa Coilzak metal mirror approach shown in Figure 3-3 represented our best solution for this class of reflector. It is in the high risk/big payoff category in the sense that extensive development would be required to determine its ultimate feasibility with respect to
Figure 3-2. Nominal CTE (\(\bar{\alpha}\)) Selection Guide
COILZAK PREFINISHED SHEET
- .03" THICK
- 1000A rms
AS RECEIVED

GOLD OVERCOAT

ERG FOAMED ALUMINUM CORE

QUARTZ-FILLED EPOXY

THERMAL MOMENT

\[ \tau_T = \int \epsilon_{th} \, dT \]

WICKING AND \( \epsilon_b \) UNCERTAINTY IS PROBLEM TO BE RESOLVED

FORMING DIE OF CORRECT RADIUS AND OPTICAL PRESCRIPTION

FORMING THE FACESHEETS

.03 ALUMINUM COILZAK FACESHEETS

ASSEMBLING THE SANDWICH ON THE FORMING DIE

FINISHED ALUMINUM MIRROR READY FOR OPTICAL COATING

Figure 3-3. The Alcoa Coilzak "Stamped" Metal Mirror Approach
initial forming precision (absolute surface accuracies are fractional micrometers) and thermal and/or temporal stability. This concept is truly a "stamped out" mirror since the thin facesheets and core structure are too flexible to permit any optical finishing subsequent to assembly. The Coilzak material was measured in our laboratory and was found to have a 1000 Å rms surface. This is adequate for wave = 30 micrometers performance but does not offer performance growth potential down to the 10 or less micrometer wavelength range. However, the concept should not be forgotten entirely since it may be an optimal solution for multisegment, large submillimeter-type systems and does not require (or permit) any subsequent optical finishing operations.

Another concern with these materials, though, was the bending potential caused by uneven bondlines between the front and rear faces and the core and the resultant thermal moment. This is treated in Appendix C, Final Briefing. Besides this macro issue were also the questions of orthotropy and residual strain, questions which, singly and in combination, have plagued the precision metal mirrors despite their appeal as potentially very low cost solutions. Regarding orthotropy in a thin shell mirror made of rolled material such as aluminum, this property will result in an astigmatic wavefront error whose value can be estimated by

\[ \Delta W F_{\text{ASTIG}} = \frac{r^2(ax - ay)\Delta T}{4h} \]

where \( r \) and \( h \) are the radius and thickness of the panel, respectively. For a maximum wavefront error of 0.5 micrometer rms, \( ax - ay \) for a 1.5 cm diameter thin shell cannot exceed \( 1.3 \times 10^{-10} \) in/in/°F. For aluminum, whose nominal CTE is \( 12 \times 10^{-6} \), this amounts to 1 part in \( 10^5 \), which is beyond the range of measurement with this material. Quartz, on the other hand, needs to be isotropic to only 1.5 parts in a thousand, which is within the observed, or inferred, results from a wide variety of optical test sources.

What about composites? One could mold segments against master forms (for each radial zone of the reflector) and bypass the traditional optical shop — and accomplish this with a "near-zero" CTE material! Unfortunately, composites will not pass the \( \Delta R/R \) criteria. Referring back to the \( \Delta \phi \) equation, the required faceplate matching for a family of sandwich panels was calculated and compared to average part-to-part CTE variations achieved with graphite epoxy structures on the Space Telescope Program.
These results are shown in Figure 3-4. A great deal of effort was expended on that program, particularly with the metering truss, to understand and control all of the process variables and minimize CTE variations. Even so, this degree of control would not be adequate or even possible for a 32-inch-thick, 40-inch-diameter mirror! Of course, such proportions are absurd and many other factors in addition to simple plate bending would need to be evaluated with such a design.

This is not to say that composites might not be adequate for a monolithic submillimeter (or IR) primary mirror. In such an instance, the segment-to-segment coherence issue is absent and with it, the $\Delta \alpha$ mismatch problem.

### 3.3 SEMI-REPLICATED SANDWICH MIRRORS

The obvious advantage of thin shells is their compatibility with the replicating or drape-molding process, and hence cost and schedule minimization. Their success demands close control of through-the-thickness CTE homogeneity within a part and on a part-to-part basis, as discussed earlier. Special techniques would need to be developed to support these panels in a strain-free state during optical shop figuring and/or shining operations. This issue would yield to an engineering development program. So, too, would the problems of mounting and attachment, coating stress negation or balancing, and handling. Low natural frequencies remain a drawback in sizes in excess of 1.5m and areal densities less than 17 or 18 kg/m$^2$. The first mode of a 2m thin shell mirror whose areal density is 18 kg/m$^2$ was calculated to be only 10.3 cps, with the support points at optimal locations. The model and analysis from which this result was derived will be found in a later section. It did include the slight stiffening effect associated with curvature, but even so, this value is judged to be too low or at best only borderline acceptable considering the frequency reductions associated with mount and attachment hardware flexibility.

To increase rigidity and hence facilitate the figuring process as well as to solve the low frequency problem, we began looking at more traditional approaches, namely sandwich mirrors. Obviously, distributing a total equivalent solid thickness of 0.2 to 0.3 inches or so of glass into a sandwich form will result in a relatively fragile structure. This perceived fragility limits the amount of material that could be removed at reasonable generating rates unless we were able to couple the core structure to a preformed off-axis aspheric faceplate and then add a backplate to this "stack".
Figure 3-4. Graphite-Epoxy CTE Variability Limits as Applied to LDR Panels
In Figure 3-5, the basic idea for accomplishing this is illustrated. Note that the nominal asphericity and curvature is produced by drape molding a constant thickness faceplate between two matching dies in the same manner that a solid preform is produced. It should be noted that the differential sagitta between radial and tangential curvatures is as great as 0.023 inches for a 2m-diameter panel employed in a 20m overall f/1 reflector. This needs to be accounted for in establishing the nominal faceplate thickness to ensure against excessively thin regions subsequent to generating the spherical core-matching surface. It is within the proven capability of the precision mirror community to generate an initially plano-plano core structure into a constant thickness spherical shape and to match machine faceplates to conformance within several millimeters. The generation of a precision off-axis asphere on a core-only structure, however, is not practically possible. Such is the basis for this design approach and hence the purpose of Step 3 shown in the figure.

To provide proportioning or material distribution guidelines for these sandwich mirrors, relationships were developed between overall mirror thickness and core depth, core density and self weight deflection, and stress and natural frequency. For core areal densities of 10%, the ratio of total height to core height is optimum at 0.94. As lighter and lighter core structures are employed, this value increases to 0.96 where the areal density of 4%. Cross section optimization curves derived to meet a specific self-weight deflection value have the general form shown in Figure 3-6, which also shows the governing equation and defines the terms in it. From this, a family of mirror blank cross sections was designed employing 3% core densities of various cell size geometries. Based on cell size and a "quilting parameter" defined in Figure 3-7 as \( S_4/t_3 \), which ranged from two to ten thousand, faceplate thickness and overall heights consistent with a c/h value of 0.95 were determined. Within this design family are a series of cross section configurations whose overall areal densities range from 11 to 20kg/in², spanning our range of interest.

Finally, the self-weight deflection, stress, and natural frequency of 0.5-, 1-, and 2m-diameter sandwich mirrors employing these crosssections were determined. These design possibilities are shown in Figure 3-8 and reveal that 15- to 20kg/m² mirrors are within the bounds of acceptable performance limits. Self-weight deflection, in the sense that it influences the requirements on metrology support systems, was found to be...
Figure 3-5. How to Make a "Replicated" Sandwich Mirror
Figure 3-6. Mirror Cross Section Optimization
\[ \rho_c = \frac{25t_2}{S^2} = \frac{2t_2}{S} \]

\[ Q = \frac{S^3}{t_1} \quad \text{for} \quad 2000 < Q < 10,000 \]

<table>
<thead>
<tr>
<th>S</th>
<th>( t_2 \rho_c = 0.09 )</th>
<th>( t_1 )</th>
<th>( h = \frac{h}{0.025} )</th>
<th>( \rho_A ) (Kg/m²)</th>
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<td>0.107</td>
<td>4.28</td>
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<td>0.137</td>
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<tr>
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<td>0.167</td>
<td>6.7</td>
<td>29.3</td>
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<td>2</td>
<td>0.02</td>
<td>0.2</td>
<td>8</td>
<td>35</td>
</tr>
<tr>
<td>2.25</td>
<td>0.034</td>
<td>0.234</td>
<td>9.36</td>
<td>41</td>
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</table>

HERAEUS 3% CORES AND F-E QUILTING AVOIDANCE WILL RESULT IN SUPER LITE-WEIGHT MIRRORS

Figure 3-7. Static Deflection for a Family of Ultralightweight Mirrors
Figure 3-3. Static Deflection for a Family of Ultralightweight Mirrors (Material is fused quartz; c/h = 0.95; for all configurations \( \sigma \leq 1000 \text{ psi @ } 10g \))
the principal design limitation. Experience gained on the Space Telescope Program with a precision metrology mount showed that the uncertainty in self-weight deflection compensation was 1/3750th the peak-to-peak deflection itself.

Thus, for a wave/125 rms WF error (wave/250 figure) at wave = 2.8 micrometers attributable to gravity release uncertainties, the self-weight or static deflection of the mirror must not exceed:

\[ \Delta L_g \leq \frac{2.8}{250} \times 3750 \times (39.37 \times 10^{-6}) = 0.0017 \text{ inches} \]

as indicated in the figure.

Our next step was to meet with the leading glass houses, Corning, Schott, and Heraeus, to review the producibility issues raised by these exceptionally lightweight mirrors. Both Heraeus and Corning have already produced small cores and mirrors in this lightness range. The "newness" introduced on this program is quantity and size, and associated with the latter, the semi-replication idea, i.e., the die forming and subsequent sphericization of the core mating surfaces.

Summarizing, we believe that there are several materials in production today which satisfy the CTE and CTE homogeneity requirements for LDR mirror panels as defined in Table 3-1. The issues requiring further development or investigation include proof of large-scale replicability, optical operations on thin, flexible substrates, and the economics of production facilities to support a delivery rate of one panel every two weeks.

In the next section, the influence of flexibility on optical operations will be discussed from an analytical aspect along with additional performance estimates relevant to thermal and dynamics issues.
4.1 OVERVIEW

In this section, we will review the key technologies that would need to be developed to support an LDR panel acquisition program. These technology issues are grouped according to materials as shown in Figure 4-1 and reveal the degree of developmental work required as well as where the major risk areas might be for these basic material classes.

We have employed a three-level evaluation code in this figure. The first, indicated by a solid circle, signifies that developmental work is required to resolve the technical issue but that its impact on the program is one of degree rather than "go" or "no-go". The last category, an open circle, is indicative of high risk area, one where an "invention" or major advance in the state-of-the-art is required. This demands an intensive development program. The second category is simply midway between these two.

4.2 METAL AND COMPOSITE MIRROR TECHNOLOGIES

Quickly scanning the figure, one sees that the glasses have the highest performance potential but that composites offer the best producibility solution. However, for the reasons described in Section 2, we do not believe that they could meet the stability requirements imposed by the $\Delta$ R/R coherence criteria over the wide temperature change between factory and operation. We believe that the inherent characteristics of (graphite-epoxy) laminates are such that their development as an LDR segment material should be discouraged.

Metals, in this case hot isostatically pressed (HIPd) I-70 beryllium, have better performance potential than composites with regard to R/R by virtue of homogeneity. In terms of availability, 0.4m HIPd beryllium mirrors have already been produced and tested by Perkin-Elmer, demonstrating that in sizes larger than "test coupons" the
<table>
<thead>
<tr>
<th>TECHNOLOGY ISSUES</th>
<th>GLASSES</th>
<th>GLASS/CERAMICS</th>
<th>METALS</th>
<th>COMPOSITES</th>
</tr>
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<tr>
<td>PERFORMANCE</td>
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<td>○</td>
<td>○</td>
<td>●</td>
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<tr>
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</tbody>
</table>

● DEVELOPMENT REQUIRED
○ SEE TEXT
○ INTENSIVE DEVELOPMENT, HIGH RISK

Figure 4-1. Candidate Materials
availability of the material is assured. While tests indicated that the figure of these test mirrors were stable down to near-cryogenic temperatures, no data exist relative to their gross (ΔR) deformation characteristics nor have enough samples been produced to assess part-to-part homogeneity, the Δα' issue described earlier. As a result, their ultimate performance compliance with the LDR coherence requirements is still unknown. Because this material is of prime interest to other government programs and because funding is anticipated from them, we recommend only that the LDR program be kept informed of progress in this area.

Facilities do not presently exist for producing panels larger than 1.4m (this size can be fabricated at Battelle in Columbus, Ohio). In fact, the development and qualification of an autoclave capable of 15000°F and 15000 psi performance is crucial to the consideration of this material. The up-front costs are estimated to be in the $10M to $15M range. Issues to be resolved regarding HIPd (thin shell) mirror panels include the Δα' parameter and forming accuracy, both of which are highly dependent on the autoclave and compaction processes, before further consideration is given to this material. The parameter could be assessed using the same equipment envisaged to make these measurements on the glass and glassy ceramic candidate materials (this equipment will be discussed shortly).

The advantage of HIPd beryllium over the glasses may reside in cost and schedule. The cost of a HIPd blank ready for optical finishing is on the order of $1250/lb., based on the several pieces already fabricated by Perkin-Elmer. For a 15,000 lb. total panel weight, the blank costs would be $19M and delivery rates would (probably) be faster than they could be processed through the optical shop(s). Glass cost estimates, using fused quartz as an upper bound baseline, range from about $11M for 1.5m thin shells to $45M for sandwiches. These numbers are predicated on a 25m overall reflector diameter where 560 trapezoidal segments are employed. The delivery rates for fused quartz blanks are also nowhere near competitive with the beryllium potential, but they may be rapid enough to be compatible with optical shop capabilities.

Despite the potential attractiveness of beryllium from a producibility or fabrication aspect, we do not deem it a "prime" candidate at this time because of performance (homogeneity) uncertainties. It should be mentioned that cryo null figuring, subsequent
to a thermal strain relief cycle, might offset the (potential) homogeneity issue but at greatly increased optical fabrication time.

4.3 GLASS AND GLASSY-CERAMIC TECHNOLOGY

As stated in Section 2, glasses and glassy-ceramics are the recommended materials. They include fused quartz, Zerodur, Pyrex, and Duran. These materials all are in the minimal performance risk category. The problems to be solved to make them fully compliant with the requirements of the LDR Program reside in rapid and high quantity production and in lightweighting, where these two factors are not mutually exclusive. Fused quartz, for example, virtually guarantees performance, if we can make the mirror blanks light enough and rapidly enough. Thus, the emphasis for continued panel development should be on these issues rather than materials development itself.

4.3.1 Material Testing

One aspect of this effort must deal with the thin shell vs. ultralightweight sandwich decision, specifically the $\Delta\alpha'$ question. A modest development effort is recommended to verify that the Heraeus Fused Quartz material does indeed meet this crucial homogeneity requirement and that such mechanical processing as grinding does not produce internal strain unbalances, and also that coatings are sufficiently strain-free and athermalized to ensure adequate dimensional stability for a thin shell. We would also recommend that alternative materials to fused quartz be verified as a cost reduction goal and as a second source for mirror blanks to enable parallel procurement. It is not necessary that all the panels in a segmented mirror be constructed of the same material. Pyrex, Zerodur, and Duran are potentially less costly alternative materials. In Section 6, several concepts for assessing the $\Delta\alpha'$ parameter over a temperature range from RT to -100°F will be described.

4.3.2 Fabrication Technologies

As stated earlier, the LDR mirror blanks are deemed too fragile for machine generation at reasonable material removal rates. That, as you will recall, was the thrust behind the semi-replication approach. The goal of our approach is to obtain curvatures of sufficient accuracy from the blank manufacturer to enable us to proceed directly to our small and light tool Computer Controlled Polisher and thus obviate the quilting, or mechanical damage, problem.
Forming precision, because of the high temperatures involved, is expected to be most critical with fused quartz. Pyrex, Duran, and Zerodur are all formable at lower temperatures and if the techniques are perfected for quartz, the extension (or retraction!) of the technology to these other materials is relatively straightforward. We show in Figure 4-1 this forming issue as being in the third, or most critical, category. Development work in this area is applicable to both thin shells and sandwich configurations.

When dealing with sandwich mirrors, quilting avoidance at rapid material removal rates will require tool development tests and other related processing techniques such as the "Quilting Post" described in Section 6. The issue here is not whether it can be done, but whether it can be done quickly. Assuming for argument that all the panels need to be fabricated within a six-year period, beginning with a 1987 proof-of-concept demonstration and culminating in a mid-1995 flight date target, mirrors would need to be finished at the rate of two per week (in the 1m size for a 20m reflector). Once more, the importance of "replication" and rapid, quilt-free material removal is strikingly apparent.

Related to optical shop operations also is the ability to directly interface an as-received, semi-replicated surface directly with the CCP (or equivalent machine). Two factors are dominant in this regard. One is how to measure the surface shape in order to be able to generate the machine command program (i.e., the material removal profile) despite the fact that the surface is diffuse and (optically) irregular which precludes the use of interferometric, Hartman, and related reflective and/or imaging techniques. Actually, this can be done by mechanical means for wave = 30 micrometer mirrors with sufficient accuracy, as will be shown in the next section. The development of this measuring system is needed for the LDR Program. Transition to more conventional metrology, if required, would occur after the blank had achieved the near-desired figure and specular surface.

Characterization of the non-specular, as-received surface we believe will yield to the above referenced solution or one like it. The second factor pertains to the ability of the CCP machine to correct what are potentially high spatial frequency errors in the as-received blank without destroying the formed or replicated off-axis aspheric shape. Tool size and conformability to the changing curvature of the aspheric surface as well as tool path velocity control are involved in this issue.
Consider a 20m, f/0.5 reflector where the sagittal and tangential radii of curvatures at a point half a meter in from the edge are 22 and 27 meters respectively. For a tool diameter of 0.025m (1 inch), the difference in sagitta under the tool would be 0.7 micrometer (26 x 10^{-6} inches). This is equivalent to 0.023 wave at \( \lambda = 30 \) micrometers or 0.35 wave at \( \lambda = 2 \) micrometers peak-to-peak. The latter value (which is equivalent to about a wave/2.5 rms value in the visible for reference) is indicative of the surface quality that would be achieved with the initial grinding tools used to "clean up" the as-received mirror blanks. Subsequent tools will need to be somewhat larger and more compliant to remove the cusps left by the initial tooling as the higher quality final surface is approached. The development of this grinding and polishing technology is recommended as a high priority activity. It is a mandatory adjunct to the concept of semi-replication which, in turn, is the basis of the LDR panel fabrication approach.
SECTION 5

ANALYTIC STUDIES

5.1 STRUCTURAL MODELING

For the most part, deflection, thermal bending, and stress trades and sizing studies were performed using closed form solutions for flat plates. The bulk of these study results is found in Appendix B. However, a finite element model of a "typical" trapezoidal panel was constructed to verify these closed form solutions, particularly with regard to the effects of initial curvature on thermal bending (corner curl phenomena) and frequency. In addition, this model provided a rapid means for evaluating alternative support point location options.

Some general results from this finite element model investigation will be stated below:

a. Initial curvature had no significant effect on panel stiffness when 2m panels were employed with a 20m, f/2 reflector. As the reflector became "faster", say f/1.5, then about a 10% stiffening effect was observed. At f/0.75 the stiffening effect was approximately 1.3. These results are applicable to thin shell mirrors only; structural or sandwich mirrors did not exhibit any stiffening effect within the LDR range of geometry. This would be expected since the sagitta of a 2m panel employed in a 20m, f/0.75 reflector (R=30m), for example, would be 0.033m (1.3 inches) which is less than half the thickness of a "typical" sandwich panel. Obviously, it represents a large initial curvature in a thin shell of 8mm (0.3 inches) thickness. Therefore, to a certain extent the frequencies calculated in the trade studies for thin shells (Appendix B) are conservative by about 25 to 30%.

b. For trapezoidal (square) thin shell panels, no "corner curl" was observed. It was feared that circumferential discontinuities or internal hoop stress in these initial curved shells might cause anomalous behavior when subjected to a uniform bending moment, such as caused by an axial \(\alpha'\Delta T\). The
occurrence of such a non-spherical bending term would have been significant in that it might have eliminated thin shells from further consideration.

c. The trade studies assumed three-point edge support for frequency calculations. Moving the support inboard, as shown in Figure 5-1, resulted in almost a 2x frequency increase. For example, the closed form/edge support solution for this showed a first mode of 5.45 cps. The FEM solution with inboard support demonstrated that this could be raised to 0.26 cps. At this stage the sensitivity to small changes in the support location has not been performed, nor have any preliminary design concepts for the support hardware been identified. The conclusions obtained from this point design example, though, do confirm the mechanical viability of thin shells. Considerably more work needs to be performed, however, to support a final concept decision. This work would include mount location optimization for 1 1/2- and 2m panels of both 0.25, 0.35, and 0.45-inch thicknesses from a stress and frequency aspect, the effect of secondary mount constraint forces on figure precision, and the development of attachment concepts for thin shells.

5.2 THERMAL ANALYSIS

This section summarizes the relevant temperature change conditions important to panel design and material selection. It is based on a thermal shroud concept with an L/D ratio on the order of 1.5:1 and assumes a 400nm circular orbit in the plane of the ecliptic where earth viewing will occur for approximately 50% of the time. Only by using a large shroud, in contrast to a simple sunshade, were we able to passively provide a relatively cool 200K environment for the reflector and to limit diametrical gradients to insignificantly small values. The basis of this shroud design concept is shown in Figure 5-2, and in Figure 5-3 the influence of the shroud's length to diameter ratio on the total amount of energy observed by the reflector when occulted by the earth is shown. The performance of this shroud concept is summarized in Table 5-1.

As previously stated, the LDR shroud was conceptually designed with two major requirements in mind: to minimize the reflector temperature passively and to minimize the side-to-side variation across the LDR diameter such that the lateral temperature gradients across an individual panel are negligible.
6/11/82 MAX-DEF. = 9.04840640
2 METER SEGMENT

2M F-10.0 SEGMENT LDR
FINAL SYSTEM DESIGN - 20M SYSTEM F-1.0
MODAL DEFOR. SUBCASE 1 MODE 1 FREQ.
10.26792

E = 9.8 X 10^6
\rho = .079
\tau = .3 \text{ IN}
R = 40 \text{ m}

Figure 5-1. Support Moved Inboard Resulted in a Nearly 2X Frequency Increase
Figure 5-2. LDR Enclosure Design Concept

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Material Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>External Enclosure</td>
<td>☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐</td>
</tr>
<tr>
<td>Internal Enclosure</td>
<td>☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐</td>
</tr>
<tr>
<td>LDR</td>
<td>☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐</td>
</tr>
</tbody>
</table>

Thermal Radiation Parameters:
- Eliminates the possibility of the sun irradiating the interior.
- Provides an area for earth IR and albedo energy rejection.
- Minimizes side-to-side gradient with MLI gradient change.
- Controls internal irradiation absorbed by the LDR.

Parameters:
- Length (L)
- Material
- Sun shade
- Radiation/Shaft
- Enclosure
- Forward Enclosure
- MLI

Diagram:

[Diagram showing LDR, mirror, and forward enclosure]
TABLE 5-1
LDR ENCLOSURE TEMPERATURE

- FORWARD ENCLOSURE TEMPERATURE
  Configuration/Temperature °F
<table>
<thead>
<tr>
<th>Configuration</th>
<th>Maximum</th>
<th>Minimum</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Radiator</td>
<td>83</td>
<td>-460</td>
<td>-145</td>
</tr>
<tr>
<td>Albedo Radiator</td>
<td>44</td>
<td>-225</td>
<td>-114</td>
</tr>
<tr>
<td>Moveable Shade</td>
<td>-105</td>
<td>-127</td>
<td>-120</td>
</tr>
</tbody>
</table>

- AFT ENCLOSURE TEMPERATURE
  Configuration/Temperature °F
<table>
<thead>
<tr>
<th>Configuration</th>
<th>Maximum</th>
<th>Minimum</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Radiator</td>
<td>83</td>
<td>-460</td>
<td>-145</td>
</tr>
<tr>
<td>Albedo Radiator</td>
<td>-105</td>
<td>-127</td>
<td>-120</td>
</tr>
<tr>
<td>Moveable Shade</td>
<td>-460</td>
<td>-460</td>
<td>-460</td>
</tr>
</tbody>
</table>

- ABSORBED ENERGY
  Maximum 1.5 BTU/hr - ft²
  Side-to-side variation ≤ 10%

- SIDE-TO-SIDE GRADIENT
  Less than 1°F
The resulting design is summarized in Table 5-1. The radiators and the radiator shade provide the means to reject the reflected earth shine (albedo) and IR energy entering the aperture, thus providing for an average LDR temperature of -120°F. Radial energy variations are minimized by the 1.5D long shroud which minimizes direct irradiation of the LDR. Additionally, multi-layer insulation reduces the LDR interior environment gradients, due to the maximum exterior gradient of 500°F, to less than 10°F.

Figure 5-4 illustrates the maximum flux variation condition for the LDR. The earth has just passed from view of point "A" while point "C" is fully illuminated. The magnitude of the absorbed flux on point "C" is attenuated by the shroud so that the resulting side-to-side variation is less than 0.2 BTU/hr ft²°F.

The deployment of hardware concepts which satisfy the thermal design parameters of the shroud and also are compatible with stowage and deployment, weight, dynamics, and pointing control system requirements is envisaged as a very critical factor in the LDR Program. Performance trades between L/D and average reflector temperature as well as side-to-side temperature differences within the cavity (versus various candidate panel materials) and hardware implementation concepts unfortunately were beyond the scope of this study but should be pursued in any follow-on work.

Earlier, the desirability of insulating the rear surface of the panels with a low emissivity coating (or MLI) was identified as a means for minimizing axial temperature gradients. In subsequent analyses this concept needs to be explored in more depth, particularly with regard to (conductive) heat leaks associated with mounting and attachment hardware.

Even though the thermal work is far from complete, we can conclude that a cylindrical shroud, at least as long as the diameter, is required to attain a cold reflector. And further, the shroud will probably require some form of internal heat rejection system, the "albedo radiator" shown in Figure 5-3, to ensure both a cold and spatially uniform environment for the mirror. We do not believe that simple occulting disks or "sunshades" could achieve the low and uniform temperature requirements unless augmented by an active coolant loop flowing through the panels. This is a viable trade issue when considering the enormity of the shroud and its ramifications on the system's mechanical, dynamic, packaging, and related technical issues.
5.3 QUILTING

In the case of sandwich mirrors with uncommonly thin faceplates, such as those potentially of interest to the LDR Program as a conservative alternative to thin solids, the issue of quilting or print-through of the core is of interest. The effect of quilting is to diminish the central amplitude of the image spot and redistribute this energy into false spots, spaced away from the principal image. The relationship between quilting amplitude and the central spot energy reduction factor was derived for a square cell quilt pattern and is:

\[ \frac{M_1}{M_0} = 1 \frac{4(I(1,0)/I(0,0))}{\text{Strehl}} \]

where

\[ I(1,0)/I(0,0) = \frac{\pi^2 \sigma^2}{1 - 2\pi^2 \sigma^2} \]

and

\[ \text{Strehl} = 1 - 4\pi^2 \sigma^2, \]

and where \( \sigma \) is the rms WF error, equal to the quilt amplitude divided by two, and

\( \frac{M_1}{M_0} \) is the ratio of energy in the central spot to the energy that would have existed without quilting.

For a 3% reduction in performance the quilt amplitude cannot exceed 0.05 wave based on the above equation. For an operating wavelength of wave = 2 micrometers, this is equal to 0.1 micrometer or \( 4 \times 10^{-6} \) inches.

Quilting will occur in sandwich mirrors when one of two conditions exist. The first and generally that which is most often observed occurs during polishing when the interface pressure between the tool and mirror is spatially modulated by the presence of the ribs, which present a stiffer resistance to the tool than the center of a cell where the faceplate bending resistance is less. As a result, more material will be removed in the regions of higher interface pressure, the ribs, than over the center of the cell. This is termed "quilting." Soft tools or tools smaller than a cell are often solutions to this
issue within given ranges of practicality for a specific faceplate to span thickness. In "the world or visible optics," the space and thickness relationship, $S^4/t^3$, is generally maintained by these producibility considerations between 250 and 1000. In the case of the latter, this higher value is reserved mainly for small mirrors where lower nominal tool pressures and concomitantly reduced material removal rates can be tolerated. For the LDR class of mirror, however, where $S$ might be 1 1/2 to 2 inches and $t$ equal to 0.15 inches, $S^4/t^3$, ratios on the order of 5000 must be dealt with. This might "just be 'OK'" for a wave = 2 micrometers or 4x visible wavelength. To achieve a 4 microinch quilting limit, however, the nominal polishing pressure, calculated from "flat plate" equations, could not exceed 0.17 psi. Typically, though, pressures on the order of 0.35 to 1 psi are used to achieve reasonable schedules vis a vis material removal rates. In the next section, we will present a method for increasing the stiffness of the faceplate by a factor of 16 during the optical finishing phase without adding any weight to the mirror.

While increased tool resilience, reduced pressure, and/or small tool sizes provide a degree of anti-quilting control during polishing, not all of these are available during the grinding stage where the basic mirror shape is created. The hard grinding tools, cup wheels for example, are more aggressive quilters than the softer figuring tools or the even more resilient polishing laps. The semi-replication approach described earlier is intended to reduce the amount of material that needs to be removed during this phase.

However, quilting produced during these operations is usually not seen because the surface is too diffuse to permit optical measurements to be made. The quilting produced here, if it occurs as a result of high $S^4/t^3$ ratios or pressures, is first observed during figuring when the surface is sufficiently specular to permit interferometric measurements to be made. The faceplate stiffening method previously referred to is perhaps more important to the shaping or grinding phase than to figuring and polishing.
In the course of presenting our results for each of the specific statement of work tasks, we have identified fused quartz as the material of choice for thin shell solid mirrors. Pyrex would be a second choice but would probably be limited to sandwich forms to satisfy the $\Delta a'$ criterion. Quartz, in sandwich form, is undoubtedly the best performance-oriented solution but has schedule and/or cost drawbacks. It does virtually assure performance as a wave = 30m coherent system and as a wave = 2 micrometer "light bucket" composed of diffraction-limited, but not necessarily phase-matched, segments. We also believe that 15 to 20kg/m$^2$ sandwiches in the LDR size range of interest are within realistic expectations.

The development of these semi-replicated, off-axis, ultralightweight quartz sandwich mirrors would encompass all of the required LDR panel technologies. Reversion to thin solids or other candidate materials such as Pyrex, if feasible and/or desirable, would be a relatively simple matter if the quartz sandwich technology were a proven capability.

### 6.1 FUSED QUARTZ SANDWICH

The mirror blank shown in Figure 6-1 is illustrative of the design of such a sandwich mirror and employs a 4% areal density core. With the dimensions shown on the drawing the full circular planform version of this mirror would have a first mode of almost 100 cps if supported at three equally spaced points on the rim. The maximum faceplate stresses, at 10-g, would be 550 psi and, based on a 2000 psi allowable, the margin of safety would be +2.6. If the same cross section were employed with a 2m diameter mirror (i.e., constant areal density) the frequency and stress would be 49 cps and 1050 psi respectively. Both are acceptable values based on the criteria established in Section 2.

Implicit in the above results was fused quartz as the mirror material. To the best of our knowledge only Heraeus in West Germany can produce the dual thickness welded
Figure 6-1. Optimal LDR Mirror Panel

\[ W = 15 \, \text{kg/m}^2 \]
\[ f = 92 \, \text{cps} \]
\[ \sigma_{10g} = 515 \, \text{psi} \]
\[ \Delta_{ST} = 0.8 \lambda \text{ at } \lambda = 30 \mu \text{m} \]

MATERIAL HERAEUS FUSED QUARTZ
CORNING ALUMINO-SILICATE
eggcrate core shown in the drawing. The core itself would be joined to the faceplates with a $\Delta L/L$ matching frit which fires at a temperature well below the softening point of the quartz parent material. Fusion of the faceplates would soften them and destroy the initial precision of these replicated (i.e., accurately molded) elements.

6.2 PYREX SANDWICH CORE

If the mirror were made of Pyrex, a core structure similar to that shown in Figure 6-2 would be recommended for reasons of producibility with this material. For quilting resistance equal to that of the square grid core, the dimension $h$, or height of the equilateral triangle, can be $1.4 \times$ the cell span of the former. Hence the areal density of the triangular core is equal to:

$$P_A = 3(t/h).$$

Setting $h$ equal to 1.4 times the 1.5 inch square cell spacing, the value $t$ which is commensurate with a 4% areal density is 0.028 inches. This is (probably) too thin to enable the core to be generated to a spherical surface without fracturing some ribs. The state of the art, with very careful machine control, gives about 0.05 inches which is one of the reasons behind the Heraeus dual thickness approach. So if Pyrex were used with an 0.05-inch wall thickness, the areal density of the core would be 7%. The unit weight of the mirror would rise from 16 kg/m$^2$ to 19 kg/m$^2$, still acceptably light for an LDR reflector.

6.3 QUILTING AVOIDANCE TECHNIQUE

With these mirrors, we are dealing with quilting susceptibility values, $S_4/t_3$, of 5000. This is well beyond the range of current practice for mirrors of this size. We propose as a solution to this problem the use of a temporary faceplate reinforcing device which is referred to as the "Quilting Post." As shown in Figure 6-3, it exploits the fact that Heraeus mirrors are produced with vent holes in the center of each cell on the back surface. In principle, this could also be done with Corning Pyrex or virtually any type of sandwich mirror.

The sketch is almost self-explanatory. Basically, a temporary load path whose stiffness is nominally equal to the rib stiffness is used to reduce the unsupported faceplate span.
Figure 6-2. Pyrex Ribbon Core Mirror Construction, Feasible by Virtue of Pyrex's Highly Formable Nature
2. CYANOACRYLATE BOND FERRULE TO MIRROR. EASILY REMOVED WITH HEAT AFTER FIGURING

3. EPOXY BOND FERRULE TO TUBE

4. HEAT TO LOOSEN CYANO. AND REMOVE RODS AFTER FIGURING IS COMPLETE

1. INSTALL TUBE AND FERRULE FOR CENTERING

- 16:1 FACEPLATE STIFFNESS INCREASE
- 2.52 EQUIVALENT THICKNESS INCREASE
- FOR DIMENSIONS SHOWN, POST INCREASE $s^4/t^3$ FROM 5056 TO 316, OUT OF THE QUILTING CONCERN RANGE

Figure 6-3. How to Avoid Quilting Simply
by a factor of 2. As this span enters the deflection equations as a fourth power, the span reduction is expected to provide a $2^4$ or 16x increase in the faceplate stiffness. The selection of adhesives shown in the figure is based on the requirement that the post/ferrule assemblies be easily removed from the mirror subsequent to polishing.

6.4 SURFACE MEASURING TECHNIQUE

Figure 6-4 depicts a concept for measuring the surface of the as-received mirror blank, assumed to be non-specular. It is an adaptation of the Hewlett-Packard 5501 Laser Measuring System configured in a straightness measuring mode. We in our application are interested in the non-straightness aspect of the surface but fundamentally the approach is the same. Predicted measurement accuracies of 2 to $4 \times 10^{-5}$ in. are certainly adequate for the wave = 30 micrometers requirement and probably are satisfactory down to waves of 2 or 3 micrometers. This approach, coupled with visible or, even better, infrared interferometry as the precision of the mirror is improved in the figuring process, is how we would propose to go directly from the "box" to the CCP machine.

In the limit it would be desirable to eliminate the need for any interferometry by developing the concept to a point where it is sufficiently accurate down to wave = 2 micrometers. This is important with regard to segmented mirrors with off-axis aspheric panels which ordinarily would require a null lens for each (different) segment. It would also avoid the problems associated with centering the null lens and panel. This, of course, is a difficult problem when the panel is off-axis and has no center.
Figure 6-4. Contour Sensing of Non-Symmetric Convex Aspheric Optical Surfaces
SECTION 7

RECOMMENDED TECHNOLOGY DEVELOPMENT PLANS

7.1 SCHEDULE OBJECTIVES

This final section describes a recommended technology development plan which would lead to mechanically and thermally qualified prototype LDR panels in three years. The plan covers thin solids and sandwiches, fused quartz, and Pyrex materials, and the development of those manufacturing processes necessary to fabricate these ultralight-weight, off-axis aspheres in the 1987 - 1990 time frame. Should the LDR Program be shifted further out from a 1993 initial operational capability (as stated in the top-level system requirements) to a 1998 or 2000 period, we would probably be recommending a different plan, and perhaps also a different concept.

The thrust behind this caveat is that our plan is tailored, along with our recommended design(s), to the earlier IOC date and that to meet it we must begin critical hardware experiments now. What is precluded from consideration by this constraint are several emerging technologies which may have long-range payoff. These include ion milling and large scale selective deposition techniques which might be favorably employed for very lightweight substrates. We do not see these techniques totally as replacements for those grinding and polishing operations presently envisaged as being carried out on the CCP. Rather, they might take a hand-off from CCP when a panel is only partially completed and possibly finish it in a shorter time. In this sense, the work identified in the plan is not in jeopardy of being obsoleted by ion milling techniques (for example) but, indeed, may be a necessary adjunct.

7.2 PLAN DESCRIPTION

The plan to be described is shown in Figure 7-1. It is divided into three experimentally oriented areas plus a continued facilities scale-up and cost assessment task. The first area deals with the development of Heraeus Fused Quartz thin solid mirrors. Embedded in this are several activities also required to support semi-replicated
Figure 7-1. Ultralightweight Mirror Development Program Formulation (Sheet 1 of 2)
Figure 7-1. Ultralightweight Mirror Development Program Formulation (Sheet 2 of 2)
sandwich mirror technology and the characterization of alternate materials for thin shell mirrors, as well as demonstrating the adequacy of quartz itself. What this refers to are the through-the-thickness (T^3) homogeneity measurements to assess the Δa' thickness (T^3) parameter discussed earlier in this report.

7.2.1 Material Characterization Tests

Several approaches to accomplishing this measurement have been identified and are shown in Figures 7-2 through 7-5. In the first figure, the bending of a beam-like specimen as a consequence of bulk average temperature change would be measured using a precise, remote sensing apparatus such as a Hewlett-Packard Laser Measurement System. Measurements would be made following the sequence shown in Figure 7-3 to detect and negate any experimental biases. An alternate scheme employing holography has also been identified and might result in a time savings since only one setup is required per specimen. As shown in Figure 7-4 (sheet 2), the effect of such experimental biases as non-uniform specimen temperatures could be back out of the experimental data directly. These experiments would be performed on sample populations of as-received/optically polished, and on optically polished/coated fused quartz specimens. Subsequently, Pyrex, Duran, Zerodur, or metals could/would be evaluated to assess T^3.

7.2.2 Material Removal Experiments

The ability of the CCP process to directly attack the as-molded surface with its high spatial frequency error content also is a fundamental element of the semi-replication process requiring development and demonstration. This activity could be combined with the quilting avoidance task by supporting the work piece, as shown in Figure 7-5. The objective here is to develop the CCP technology to the point where the as-received surface could be optically "cleaned up" without having to resort to first producing a spherical surface with large tools. Rather, the as-molded asphere would be worked on directly without losing its basic shape. Part of this effort would also be to learn how to do it rapidly which, of course, is interdependent with the quilting issue. Finally, in this same sphere of development is the issue of strain-free support of very lightweight, easily deformed mirrors during the figuring process. We believe that a dual support approach might best be employed here. A relatively rigid support might be employed to
Figure 7-2. Apparatus for Thru-the-Thickness CTE Measurements
Figure 7-3. Experiment Sequence

SET-UP NO. 1

SIDE A

ROOM TEMPERATURE INITIAL READINGS

READS MADE DOWN TO -100°F

TEMPERATURE BROUGHT BACK TO R.T. TO DETECT SPECIMEN OR APPARATUS HYSTERESIS

SET-UP NO. 2

SIDE A

SPECIMEN INVERTED

TEMPERATURE DROPPED TO -100°F

AND BACK TO R.T.
Figure 7-4. Alternative Measurements Concept #1 (Sheet 1 of 2)
HOW TO KEEP THE INFLUENCE OF AXIAL TEMPERATURE GRADIENTS ($\Delta T^2$) FROM FOULING UP THE DATA.

MEASURE BOTH PARTS SIMULTANEOUSLY, i.e., IDENTICAL THERMAL CONDITIONS:

\[
\delta_1 = \frac{\xi^2 \alpha \Delta T^1}{8h} + \frac{\xi^2 \Delta g \Delta T}{8h} \\
\delta_1 = c_1 \Delta T^1 + c_2 \Delta \alpha \\
:\Delta \alpha = \frac{\delta_1 - \delta_2}{2c_2}
\]

AND

\[
\delta_2 = \frac{\xi^2 \alpha \Delta T^1}{8h} - \frac{\xi^2 \Delta g \Delta T}{8h} \\
\delta_2 = c_1 \Delta T^1 - c_2 \Delta \alpha \\
\Delta \alpha = \frac{\delta_1 - \delta_2}{2c_2}
\]

\[
\Delta \alpha = \frac{4(\delta_1 - \delta_2)}{\xi^2 \Delta T}
\]

Figure 7-4. Alternative Measurements Concept #1 (Sheet 2 of 2)
HERAEUS FURNISHED SEMI-REPLICATED QUARTZ SUBSTRATE

FILLER MEDIUM
(THICKNESS GREATLY EXAGGERATED)

PVA PARTING AGENT

EXAGERATED SURFACE UNDULATION

"QUILTING POST" SIMULATION (SEE PLAN TEXT)

*R 4/t 3 = 5000 SIMULATING A FULL SCALE .1" FACEPLATE,
1.5" CELL MIRROR

Figure 7-5. Shell in Tooling Fixture (Concept Only)
hold the piece during actual grinding and polishing operations while a precision
metrology mount would "float" the mirror during figure measurement. Subsequently it
would be transferred back to the stiff mount for additional material removal. Most of
this CCP development work could be performed using "thin shells of opportunity" and
special pieces would not have to be procured. Several such shells were produced by
Heraeus and are presently at Perkin-Elmer. They are 16 inches in diameter, 0.13 inches
thick and are approximately f/2.5. They were molded over graphite dies in the manner
described earlier in this report.

7.2.3 Mirror Fabrication

Presuming success in being able to interface the CCP directly with the as-received
shells, supported in principle as shown in Figure 7-5, the ability to figure sandwich
mirrors would be, to a large extent, demonstrated. It would then be necessary to
demonstrate the fabricability of semi-replicated sandwich mirror blanks according to
the concept shown in Figure 3-5. The bulk of this activity could be deferred to the
second year of the planned development program. During this year, too, and assuming
that the T^3 testing program confirmed (at least) fused quartz as a suitable material, we
would recommend figure thermal stability tests to be performed on a 1m thin shell
mirror. During the first year, in preparation for this molding process, development
work should be supported at Heraeus. Remember, if the process can be developed for
quartz and its concomitant high temperatures, confidence in process success for lower
temperature softening materials should be very high. We would expect that several 1m
spheres or aspheres would be produced by Heraeus that year for figuring and testing in
the second.

Some of these faceplates would be used for fabricating the sandwich quartz mirror. If
funds permit, an alternative to quartz, namely Pyrex, should be pressured at Corning as
a potential cover-cost option. Finally, in the third year the quartz sandwich mirror
blank which was assembled in the second year would be figured and subjected to the full
spectrum of structural and thermal qualification tests. If all the elements in this plan
were funded and were successful, at this point in time we would have a 1m fused quartz
thin shell, a 1m fused quartz sandwich, and optical performance data for both of them
at the system operating temperature. Whether or not their inherent performance
characteristics define an ultimate decision or if the solid vs. sandwich choice resides
with overall system design and facilities/cost studies, for the technology to produce these mirrors will have been demonstrated.

7.3 Summary

In summary, the first year of this plan is directed towards fundamental technology issues:

i. $T^3$ measurements

ii. accuracy attainable

iii. thin facesheet/core joining techniques

iv. CCP interfacing and rapid quilt-free material removal.

These are denoted by the (†) symbol in the figure. The second year will result in a figured and tested thin shell and the third year will result in an off-axis aspheric 1m $\text{mirror}$ of about 15 to 20kg/m$^2$.

The cost of implementing such a plan has been estimated at between $3M and $5M, including continued design and performance analyses and facilities utilization and scale-up studies. The direct experimental costs are on the order of 300K, 650K, and 1000K for the three years respectively.

The plan is flexible in that certain elements are essentially stand-alone technologies and could be funded as isolated projects if funding constraints so required. For example the Optical Stylus (or an equivalent approach) could be developed independently, and the $T^3$ measurements could be treated as a separate investigation, as could the quilting avoidance experiments. However, they must all be successfully completed prior to embarking on the actual fabrication of shell and sandwich mirrors. It should also be noted that very little additional funding is required to develop the shells since the forming technology is required for the semi-replicated sandwiches as well. Expressed somewhat differently, the shells are a very-low-cost spinoff from the sandwich development effort.
LDR
SEGMENT TECHNOLOGY ASSESSMENT
STUDY

FIRST BRIEFING
APPENDIX A

FIRST BRIEFING
LDR
SEGMENT TECHNOLOGY ASSESSMENT STUDY
FIRST BRIEFING 10/15/81
PERKIN-ELMER
OTD
PERKIN-ELMER
LDR KICKOFF MEETING AGENDA
OCTOBER 15, 1981
NASA AMES

1. INTRODUCTION

2. SCIENCE OBJECTIVES

3. STUDY OBJECTIVES OVERVIEW
   - OVERALL SYSTEM REQUIREMENTS
   - OVERALL PROGRAM MILESTONES
   - STUDY FLOW DIAGRAM
   - PROGRAM PLAN
   - SUPPLEMENTAL EFFORT

4. STUDY TASKS
   TASK I - EVALUATION CRITERIA
     - SYSTEMS
     - MATERIALS
     - CONFIGURATIONS
   TASK II - ASSESS TECHNOLOGY
     - PROGRAMS
     - TECHNOLOGY INTERCHANGE
     - LITERATURE SEARCH
     - CONTACT LIST
   TASK III - IDENTIFICATION & EVALUATION OF PRIME TECH.
     - CONFIGURATIONS
     - MATERIALS
   TASK IV - DEVELOPMENT OF DETAILED MODELS/TRADEOFFS
   TASK V - DEFINITION OF PROMISING DESIGNS
   TASK VI - DEFINITION OF TECHNOLOGY DEVELOPMENT PLAN

5. NEAR TERM ACTIVITIES
   - TOLERANCING SEGMENTED MIRRORS
   - SPECIFIC PERFORMANCE REQUIREMENTS

6. CONCEPT SAMPLES
   - UNUSUALLY LIGHT MIRRORS
   - PRODUCIBILITY SOLUTIONS

7. DISCUSSION
LDR SEGMENT TECHNOLOGY PROGRAM

DETERMINE TWO MOST PROMISING CONCEPTS
AND
PREPARE TECHNOLOGY DEVELOPMENT PLANS

- REQUIREMENTS AND EVALUATION CRITERIA — TASK 1
- ASSESS EXISTING TECHNOLOGY — TASK 2
- IDENTIFY AND EVALUATE PRIME TECHNOLOGIES — TASK 3
- ANALYTIC STUDIES AND PERFORMANCE PREDICTIONS — TASK 4
- DESIGN DEFINITION AND CONCEPT SELECTIONS — TASK 5

10/15/81 MK
TOP LEVEL LDR REQUIREMENTS
(FROM SOW & ATTACHMENTS)

OVERALL DIA. .................. 10 ≤ D ≤ 30 m
FIGURE TYPE .................. PARABOLA OR HYPERBOLA/HOT SIMPLY SPHERICAL
FIGURE QUALITY ............... D/L @ 30 μ ———— λ ———— 2.2 μ RMS or 2 μ MIRROR
13.7 RMS SYSTEM
SPEED .......................... F/.5 TO F/1
WEIGHT ....................... 25000 LBS (11360Kg)
OPERATING TEMP ............. 150 - 200°K (-100 TO -190°F)
OPERATING W/L ............... 2 μ TO 1000 μ
DYNAMICS ..................... .00035g (SLEW), F>10 cps (SPATIAL CHOPPING)
STABILITY ..................... PASSIVE SEGMENTS PREFERRED
TECHNOLOGY DEMO ......... 1987
OPERATIONAL SYS .......... 1993
DEPLOYMENT .................. SINGLE STS FLIGHT, MANUAL ASSIST OK
MISSION DURATION .......... 10 YRS
TECHNOLOGY ROADMAP

Please refer to handout
## Tier Planning Form - Monthly -

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**PERKIN-ELMER**

**10/15/81**

**MK**
### Master Planning Form - Monthly -

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6. TECHNICAL DEVELOPMENT PLAN

- Overall plan definition/obj. |
- Update for specific config's |
- Subscale cost set |
- Fullscale cost set |
- Testing & Facil. Est. |
- Test Design |
- In-House Review |
- Comprehensive Plan Details |
| o - 260 |

7. SUPPLEMENTARY EFFORTS

- 1860 |
- As Avail |
- MODEL UPDATE W/ AS H/P & H/GERTS |
- Test Prep's |
- Test Data Eval'n. |
- 10/15/84-4211 |
- MK
SUPPLEMENTAL EFFORT

OBJECTIVE

VERIFY ANALYTIC (FEM) OF HEXAGONAL SHAPED SHALLOW SPHERICAL SHELL
. EDGE CURL ISSUE
. EMPHASIS ON CUSPS

TEST PIECE

30"-40"

.1" NOMINAL
EVALUATION CRITERIA

SYSTEM COMPATIBILITY

SHUTTLE BAY STOWAGE
APPROX. 6" (.15m) SEGMENT THICKNESS
27:1 4m SEGMENTS
13:1 2m SEGMENTS

LOW FRAGILITY
COMPATIBLE WITH ON-ORBIT ASSEMBLY
ASTRONAUT HANDLING FORCES
SIZE IMPACT ON HANDLING FEASIBILITY
ALIGNMENT SENSING COMPATIBILITY
ACCOMMODATE EDGE SENSORS, RETRO-REFLECTORS

OPTICAL SYSTEM DESIGN:
EDGE GAPS/CLEAVAGE
(GENERALLY FAVORS LARGE SEGMENTS)

ABILITY TO MEET ERROR BUDGET REQUIREMENTS
RADIUS OF CURVATURE TOLERANCE
FIGURE TOLERANCE
(GENERALLY FAVORS SMALLER SEGMENTS)

Continued on Page 2
SYSTEM COMPATIBILITY - CONTINUED

METROLOGY & GRAVITY RELEASE
ON-ORBIT THERMAL VARIATIONS
SEGMENT-TO-SEGMENT
AXIAL GRADIENT VARIATIONS
BULK VARIATIONS
INTERNAL GRADIENT DISSIPATION

ERECTABILITY
EFFECT OF SIZE ON ERECTION TIME, COMPLEXITY
MOUNT INDUCED CONSTRAINT FORCES

OVERALL WEIGHT
TOTAL SYSTEM WEIGHTS
BACK-UP STR. WT. VS. SEGMENT SIZE

INHERENT RELIABILITY
GRACEFUL FAILURE MODES

CONTINUED ON PAGE 3
EVALUATION CRITERIA

MATERIAL SELECTION

PRODUCIBLE IN LARGE SIZES

1m NOW

4m 1985

PRODUCIBLE IN LARGE VOLUME

UP TO 35,000 LBS MAT'L REQ'D OVER ~ 4 YEARS

PRODUCIBLE AT ACCEPTABLE COST

ENSURE AN AFFORDABLE PROGRAM

ST MIRROR $460/LB AT RAW BLANK LEVEL

LDR GOAL ≤ $150/LB AT RAW BLANK LEVEL

LOW THERMAL DISTORTION INDEX, αCp/K

LOW DENSITY OR LITE-WEIGHT CONSTRUCTION COMPATIBILITY

JOINABILITY WHERE APPLICABLE

LOW CTE AT OPERATING TEMPERATURE

INHERENT MAT'L & PROCESS STABILITY

HOMOGENEITY

ISOTROPY

Continued on Page 4
EVALUATION CRITERIA (CONTINUED)

POLISHABILITY & SCATTER

MICROSTRUCTURE ~ 60Å  GOAL/900Å REQ

PROCESS DEPENDANT

STRENGTH OR STRUCTURALLY EFFICIENT FORM

FABRICATION COMPATIBILITY

INHERENT FORMABILITY & DIMENSIONAL FIDELITY

REDUCES FINISHING TIME & MAT'L REMOVAL

HIGH TEMPERATURE RESISTANT

COMPATIBILITY WITH COATING PROCESSES

LOW INTERNAL STRAIN

favors long term dimensional stability

NON-MAGNETIC

LOW OR ZERO OUTGASSING

VENTABILITY FOR CORE MATERIALS

MATERIAL PROPERTIES CHARACTERIZATION

ABILITY TO PERFORM PASS/FAIL INSPECTIONS

USAGE HISTORY

CAUTIOUS RELIANCE ON THIS!

MIGHT INTIMIDATE PROGRESS

Continued on Page 5
SEGMENT DESIGN CONFIGURATION CRITERIA

FACEPLATE SUPPORTABILITY (AS APPLICABLE)

CORE SPAN VS. TOOL PRESSURE UNIFORMITY

SEGMENT SIZE

INFLUENCE ON SEGMENT WEIGHT

INFLUENCE ON SUPPORT STR. WEIGHT

INFLUENCE ON THERMAL DEFORMATION

FIGURE CONTROL IMPACT

INFLUENCE ON ....FREQUENCY, STRENGTH, ......

FACEPLATE/CORE EXPANSIVITY MATCHING (AS APPLICABLE)

\[ M_t = \frac{h^2 t_f E_f \Delta T (\alpha_c - \alpha_f)}{2R(1-\nu)} \text{ in lb/in} \]

INHERENT DESIGN PROPERTY

MINIMIZATION OF MATERIAL REMOVAL

FIGURE TIME

INTERNAL STRAIN UNBALANCE

CONTINUED ON PAGE 6
SEGMENT DESIGN CONFIGURATION (CONTINUED)

COATING COMPATIBILITY
   PROCESS TEMP, VACUUM, CLEANLINESS, OUTGASSING PRODUCTS
   BI-METALLIC EFFECT & ΔR IMPACT

AVOIDANCE OF FRACTURE POTENTIALS
   PREDOMINANTLY A CORE ISSUE DUE TO FACEPLATE COUPLED STRAINS
   LIGAMENT STRESSES
   MICRO & MACRO

PERFORMANCE GROWTH POTENTIAL
   D/L CAPABILITY AT SHORTER WAVELENGTHS
   APERTURE GROWTH

TOOLING COMMONALITY BETWEEN SEGMENTS

OVERALL ISOTROPY
   CORE ORTHOGONALITY

MODELLABILITY
   ACCURATE MODELLING
PLANS

- EXISTING PROGRAMS REVIEW
- LITERATURE SEARCH
- TECHNICAL INTERCHANGE
- SUPPLIER CONTACT

10/15/81 MK
TECHNOLOGY MIRRORS AT PERKIN-ELMER

- 3-ELEMENT SEGMENTED MIRROR 30" Ø
  PERKIN-ELMER, CIRCA 1965 DEMONSTRATED CONTROLLABILITY.
- LALOS 50" X 30" OFF-AXIS PARABOLA
  MACHINE LIGHT-WEIGHTED BERYLLIUM IR APPLICATION OPTIC.
- OMEGA 72" Ø
  50% WEIGHT REDUCTION F/1.5 ULE MIRROR
  \( \lambda/40 \) RMS VISIBLE
- SPACE TELESCOPE 60" Ø
  4" THICK SOLID DEMONSTRATE FIGURING (\( \lambda/65 \))
  CAPABILITY ON FLEXIBLE SUBSTRATES
- 96" Ø
  METROLOGY MOUNT PROOF OF CONCEPT
- HALO 14" Ø
  HI-RATE VAPOR DEPOSITION ALUMINUM SHELL
- LODE 4M
  WILL DEMONSTRATE PRODUCIBILITY AND CONTROLLABILITY. HEL APPLICATION 3/4" THICK ULE.
- ANON 12" Ø
  SUPER-LIGHT SACRIFICIAL (COPPER)
  CORED HIP BERYLLIUM

Continued
FOAM CORES

AS EARLY AS 1960 AND STILL A CONSIDERATION.

ELSEWHERE:

ITEK: FUSED SILICA S/L MACHINED 24" MIRROR
ITEK: HALO GLASS/COMPOSITE 72"Ø
EK: FRITTED ULE SANDWICH 24" Ø
HERAEUS: WELDED FUSED SILICAL "SAMPLE"
SUPPLIER CONTACT LIST

CORNING GLASS WORKS
ULE
FUSED SILICA
CER-COR
Li Al Si GLASS CERAMIC

BATTelle
BERYLLIUM PROCESSING
METALS (IN GENERAL)

LOCKHEED
GRAPHITE MAGNESIUM
LI-900, 1500 STS TILE MATERIAL

SCHOTT (DUREA, PENN.)
ZEROdUR
FOAMED ZERODUR
HERAEUS-AMERSIL (SAYERVILLE, NJ)
WELDED FUSED QUARTZ

UNITED TECH (UTC)
GLASS-GRAphITE

ALCOA RESEARCH
CHEM. BRIGHTENED ALUMINUM SHEET
(80% REFLECTIVITY)
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<th>FUSED SILICA</th>
<th>TGC</th>
<th>FUSED QUARTZ</th>
<th>ZERO-DUR</th>
<th>PYREX</th>
<th>COIL-ZAK (ALUMINUM)</th>
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### SOME MATERIAL POSSIBILITIES

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**SOME MATERIAL POSSIBILITIES**

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<td>CORNING CER-COR</td>
<td>CORES</td>
<td>?</td>
<td>FAIR</td>
<td>FEASIBLE</td>
</tr>
</tbody>
</table>
NEAR-TERM ACTIVITIES

- PRIORITIZE EVALUATION CRITERIA WEIGHTING FACTORS
- IN-DEPTH TOP LEVEL REQ’TS REVIEW
  ENSURE ØA CONCLUSIONS APPROPRIATE FOR SYSTEM & SEGMENT REQ’TS
- SEGMENT-TO-SEGMENT TEMPERATURE VARIATIONS
  $\Delta T$, $\Delta T'/H$, TRANSIENTS
  KEY MAT’L SORTING ISSUE
  SEE IF ANY CANDIDATES DROP OUT!
STATIC ERROR BUDGET

D/L PERFORMANCE = \( \sqrt{1.3} \) rms

FOR \( \lambda = 30 \mu m \), 2.2 \( \mu \)m rms WF REQ'D

**WF QUALITY @ CASSEGRAIN FOCUS**
2.2 \( \mu \)m rms

- **SM**
  - 0.5 \( \mu \)m

- **PM**
  - 2.1 \( \mu \)m

- **PM/SM ALIGNMENT**
  - 0.5 \( \mu \)m

**ALIGNMENT SENSING & CONTROL**
1.2 \( \mu \)m

- **PANELS**
  - 1.7 \( \mu \)m

**FABRICATION**
1.2 \( \mu \)m

- DESIGN RESID.
  - 0.6 \( \mu \)m

- MANUFACT.
  - 1 \( \mu \)m

- **OPERATION**
  - 1.2 \( \mu \)m

- MECH.
  - 0.6 \( \mu \)m

- THERMAL
  - 1 \( \mu \)m

10/15/81 MK
SEGMENT ERROR BUDGET

MID-FREQ
1.7 μ ± rms

FABRICATION
1.2 μ

DESIGN RESID.
0.56 μ

• FIG. SPEC.
• EDGE CUTAGE

MANUFACT.
1 μ

• METROLOGY
  ΔR  5 μ
  ΔS  5 μ

• MATERIAL
  ΔR  5 μ
  ΔS  5 μ

MECH.
0.66 μ

• GRAV. REL.
• LAUNCH RESIDUALS
• MT. CONSTRAINS
• STRAIN RELAXATION
• COATING &
  BI-METALLICS 4 μ

OPERATION
1.2 μ

THERMAL
1 μ

BULK ΔT
  ΔR  0.5 μ
  ΔS  0 μ

AXIAL ΔT
  ΔR  0.5 μ
  ΔS  0 μ

LATERAL ΔT
  ΔS  0 μ

1.7 μ

DESIGN
0.66 μ

ΔR
0.95 μ

ΔS "OUP BEYOND ΔR"
1.25 μ

FAB
0.5 μ

CP'N
0.81 μ

10/15/81 MK
## Representative Segment Design Parameters

### System Aperture

<table>
<thead>
<tr>
<th>PRIMARY F/NO</th>
<th>10M</th>
<th>15M</th>
<th>30M</th>
</tr>
</thead>
<tbody>
<tr>
<td>R (m)</td>
<td>20</td>
<td>30</td>
<td>60</td>
</tr>
<tr>
<td>SEG. DIA (m)</td>
<td>2, 4</td>
<td>2, 4</td>
<td>2, 4</td>
</tr>
<tr>
<td>SEG. F/NO</td>
<td>5, 2.5</td>
<td>5, 2.5</td>
<td>5, 2.5</td>
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<tr>
<td>Δ R TOTAL (mm)</td>
<td>1.2</td>
<td>3</td>
<td>7.5</td>
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<tr>
<td>Δ R/R %</td>
<td>0.006</td>
<td>0.0014</td>
<td>0.0029</td>
</tr>
<tr>
<td>Δ S MFG (mm)</td>
<td>0.61</td>
<td>15</td>
<td>15</td>
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<tr>
<td>AREAL DENSITY</td>
<td>141</td>
<td>141</td>
<td>141</td>
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<tr>
<td>MAX THICKNESS</td>
<td>19</td>
<td>15</td>
<td>6</td>
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<tr>
<td>CTE REQ'TS</td>
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<td>5</td>
<td>1</td>
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<tr>
<td>Δ T = 20°F</td>
<td>3.2</td>
<td>1.6</td>
<td>4</td>
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<tr>
<td>Δ T²/H² = (1°F/m)</td>
<td>0.05</td>
<td>0.013</td>
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<tr>
<td>NO. REQ'D</td>
<td>19 7</td>
<td>42 16</td>
<td>217 61</td>
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</tbody>
</table>

**Notes:**
- Δ R TOTAL EQUIVALENT TO .95 λ RMS WF ERROR
- Δ T = " " " .7 μ " " "
- Δ T²/H² = " " " .7 μ " " "

**Typo:** 7°F/inch

**Correction:**
- 7°F/inch to 10°F/inch

*To/15/81 HK*
TOLERANCING SEGMENTED MIRRORS

- SEGMENT-TO-SEGMENT RADIUS OF CURVATURE MATCHING IS REQUIRED

\[ \Delta W_{F_{rms}} = \frac{1}{3} \left( \frac{r}{R} \right)^2 \Delta R \]

- NEW REQUIREMENT WITH RESPECT TO MONOLITHIC MIRRORS

\[ \Delta R = \frac{R^2 \Delta T}{h} \]

\[ \Delta W_{F_{rms}} = \frac{1}{3} \frac{K^2}{R^2} \frac{R^2 \Delta T^2}{h} \times \left( \frac{d}{2K} \right)^2 \]

\[ \Delta W_s = \frac{1}{12} \frac{K^2}{R^2} \Delta T \]
OPTIMUM MIRROR STRUCTURE DESIGN

0 DISREGARD MINIMUM FACEPLATE THICKNESS, CORE DENSITY, AND CORE CELL SIZE CONSTRAINTS.

0 OPTIMIZE STRUCTURES AND IDENTIFY BIG PAYOFF AREAS.

0 WORK WITH BLANK MANUFACTURER TO FIND PRODUCIBILITY SOLUTION FOR THE "BIG PAYOFF" AREAS.
"OMEGA IS A POINT ON THE LINE OF PROGRESS"

6:1 SOLIDS

LIGHTWEIGHTS
6:1 → 8:1

FIGURE CONTROL

OPERATIONALLY CONFIGURED DESIGNS
15:1

OMEGA
SYSTEM/PROGRAM
-DRIVEN CONCEPT

CHEAPER
FASTER
LIGHTER
BIGGER
CORE GEOMETRY – FACEPLATE RELATIONSHIP

\[ P(x) = f(\delta) \]
\[ \delta = f\left(\frac{S^4}{t^3}\right) \]

\[ \frac{S^4}{t^3} = 607 \rightarrow 640 \text{ TODAY'S EXPERIENCE} \]

BY THESE STANDARDS, \( S = 1.5 \text{ INCHES} \)
IF \( t = 0.2'' \text{ INCHES} \).

10/15/81 MK
TUBE CORE DESIGN

\[ \text{NET AREA} = .433013 \ d_0^2 \]

\[ \text{SOLID AREA} = \frac{1}{2} \frac{\pi}{4} (d_0^2 - d_i^2) \]

\[ d_i = d_0 - 2t \]
\[ d_i^2 = d_0^2 - 4d_0t + 4t^2 \]
\[ d_0^2 - d_i^2 = \frac{4}{4} - \frac{4d_0t - 4t^2}{2} \approx 4d_0t \text{ when } t \ll d_0 \]

\[ \therefore \text{SOLID AREA} = \frac{1}{2} \frac{\pi}{4} (4d_0t) \]

\[ \frac{\text{SOLID/NET}}{2 \times .433013 \ d_0^2} = 3.63 \frac{t}{d_0} \]

EXAMPLE

.18 FACESHEETS — 1” CELL SPAN j.e. \( d_0 = 1” \)

<table>
<thead>
<tr>
<th>( t )</th>
<th>( .01 )</th>
<th>( .015 )</th>
<th>( .02 )</th>
<th>( .025 )</th>
<th>( .03 )</th>
<th>( .035 )</th>
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<tr>
<td>( % \ \Delta \text{EFF} )</td>
<td>3.6</td>
<td>5.4</td>
<td>7.3</td>
<td>9.1</td>
<td>10.9</td>
<td>12.7</td>
</tr>
</tbody>
</table>

10/15/81 MK
80" MIRROR DESIGN EXAMPLE

FUSED SILICA
FRIT JOINED

- UNIT WEIGHT .035 lb/in² (24.7 Kg/m²)
- OK FOR A 22 & 25 m SYSTEM

1" x 0.015 TUBING
(5.4% SOLID DENSITY)

WEIGHT

\[ W = \frac{\pi}{4} \times 30 ^ 2 \times \rho (2t_f + n h_c) = 176 \text{ lbs} \]

STRESS @ 12.9 ULT

\[ \sigma = \frac{Wgt}{t_e^2} = 865 \text{ psi} \]

DEFL'N @ 1g

\[ \Delta = 0.036 \frac{Wl^2}{E t^3} \times 12(1-u^2) = 0.00171'' (1.42\times) \text{ @ } 30w \]

FREQ

\[ f = \frac{1}{2\pi} \sqrt{\frac{25kIq}{Wl^2}} = 72 \text{ ops} \]

45

10/15/81 MK
CHANGING DIAMETER TO 160"

W = 704 LBS

STRESS $\sigma = 3463$ PSI

DEFL'N $\Delta = 0.0272''$ (22 $\mu$ a 30 $\mu$)

FREQ $F_1 = 18$ CPS
THIN SHELL
WAX, PITCH, CERROBEND, ...

HOLDING TOOL
FIGURING & METROLOGY

SEPARATE, ANTICIPATE, WARPAGE

IT CAN BE COERCED BACK TO SHAPE

OPTION TO ADJUST R AVAILABLE

R

STRUCTURE MADE FROM SOME MATERIAL WHICH HAS ALL ATTRIBUTES OF GOOD MIRROR MATERIAL EXCEPT IT'S NOT POLISHABLE

- IT MIGHT MATCHES THIN SHELL
- LONG TERM STABILITY
- LIGHT, EFFICIENT PACKS
- LOW COST (REL. TO GLASS)
- DUAL-D GRAPHITE EPOXY TRUSS
- GRAPHITE MAGNESIUM (LMSC)

HYBRID MIRROR

10/15/81 MK
ISSUES:
- Adhesives
- Thickness uniformity
- Bending moment
- Spring back
- Outgassing/coating ch. compatibility

Areal density: $0.01 \text{ lb/in}^2 (6.3 \text{ kg/m}^2)$

Alum. segments for well controlled thermal env't

i.e. $\Delta T \leq 5^\circ F$, $\Delta T/\text{hr} \leq 0.004^\circ F/\text{hr}$ or $\Delta T \leq 0.01^\circ F$
ARE THERE ANY QUESTIONS?
LDR
SEGMENTED MIRROR TECHNOLOGY ASSESSMENT
STUDY

INTERIM REVIEW
APPENDIX B

LDR INTERIM REVIEW
LED R

SEGMENTED MIRROR TECHNOLOGY ASSESSMENT

INTERIM REVIEW

AT

NASA AMES RESEARCH CENTER
MOUNTAINVIEW, CA.

February 25, 1982

PERKIN-ELMER CORPORATION
OPTICAL TECHNOLOGY DIVISION
DANBURY, CONNECTICUT
LDR: SEGMENTED MIRROR TECHNOLOGY ASSESSMENT

INTERIM REVIEW

AGENDA

- PROGRAM OVERVIEW

- WORK ACCOMPLISHED PER TASK AREA
  1. EVALUATION CRITERIA
  2. EVALUATE CURRENT TECHNOLOGY
  3. IDENTIFY & EVALUATE PRIME TECHNOLOGIES
  4. ANALYTIC STUDIES
     STRUCTURAL
     THERMAL

- PLANNED PE EXPERIMENT
SPEAKERS AGENDA

- Program Overview
- Evaluation Criteria
- Current Technology Assessment
- Identify & Evaluate Prime Technologies
- Analytic Studies
- Structures
- Thermal
- Panel Discussion
PROGRAM OVERVIEW

PROGRAM OBJECTIVES & TASK STRUCTURE

PANEL REQS SYNOPSIS

THE A&R ISSUE AND OTHER

KEY TECHNICAL ISSUES
OBJECTIVE: IDENTIFY 2 MOST PROMISING CANDIDATES & PREPARE DEVELOPMENT PLANS.
TOP LEVEL LDR REQUIREMENTS
(FROM SOW & ATTACHMENTS)

OVERALL DIA..................10 ≤ D ≤ 30 m
FIGURE TYPE................PARABOLA OR HYPERBOLA/NOT SIMPLY SPHERICAL
FIGURE QUALITY..............D/L @ 30 μ → λ
\[ \frac{\lambda}{13.7} \] RMS OR 2.2 μ \[ \text{SYSTEM RMS} \]
MIRROR
SPEED.........................F/4.5 TO F/1
WEIGHT.........................25000 LBS (11360KG)
OPERATING TEMP.............150 - 200°C (-100 TO -190°F)
OPERATING W/L...............2 μ TO 1000 μ
DYNAMICS....................0.00035g (SLEW), F>10 CPS (SPATIAL CHOPPING)
STABILITY....................PASSIVE SEGMENTS PREFERRED
TECHNOLOGY DEMO............1987
OPERATIONAL SYS...........1993
DEPLOYMENT..................SINGLE STS FLIGHT, MANUAL ASSIST OK
MISSION DURATION...........10 YRS

10/15/81 HK
STATIC ERROR BUDGET

D/L PERFORMANCE = \sqrt{13.7} \text{ rms}

For \lambda = 30 \mu m, 2.2 \mu m \text{ rms WF Req'd}

WF QUALITY @ CASSEGRAIN FOCUS
2.2 \mu m \text{ rms}

SM
0.5 \mu m

PM
2.1 \mu m

PM/SM ALIGNMENT
0.5 \mu m

ALIGNMENT
SENSING & CONTROL
1.2 \mu m

PANELS
1.7 \mu m

FABRICATION
1.2 \mu m

OPERATION
1.2 \mu m

DESD RESID.
0.66 \mu m

MANUFACT.
1 \mu m

MECH.
0.63 \mu m

THERMAL
1 \mu m
SEGMENT ERROR BUDGET

PANELS
1.7 \( \mu \) rms WF

FABRICATION
1.2 \( \mu \)
- DESIGN RESID.
  0.66 \( \mu \)
- MANUFACT.
  1.0

OPERATION
1.2 \( \mu \)
- MECH.
  0.66 \( \mu \)
- THERMAL
  1.0
- METROLOGY
  \( \Delta R \) 0.5 \( \mu \)
  \( \Delta S \) 0.5 \( \mu \)
- MILITARY REL.
  RESIDUALS
- FEASIBILITY
- MATERIAL RE.
  MOVABLE, QUILT
- STRAIN RELAXATION
- CONTIG, B.
  BI-METALLICS 0.4 \( \mu \)

\( \Delta S \) (\( \ldots \) 00 BEYOND \( \Delta R \))
1.25 \( \mu \)

DESIGN
0.66 \( \mu \)
- FAB
  0.5 \( \mu \)
- GF
  0.81 \( \mu \)

10/15/81 ME
RADIUS OF CURVATURE PRECISION:

THE ΔR ISSUE FOR COHERENT APERTURES

\[ \Delta W F_{\text{rms}} \approx \frac{1}{3} \left( \frac{\Delta R}{R} \right)^2 \leq 0.95 \mu \text{rms} \left( \frac{\Delta R}{R} = 0.3 \mu \right) \]

INITIAL MANUFACTURE & OPERATIONAL EFFECTS \( \Delta R/R \) BUDGET

\( \Delta R/R \) \( .000050 \) to \( .000200 \)

~ MORE DISCUSSION LATER ~
KEY STUDY ISSUES

PASSIVE STABILITY: FIGURE 9, RADIUS OF CURVATURE
- RELATIONSHIP TO WEIGHT, THINNESS, & SEGMENT SIZE
- METALS, CERAMICS, & GLASSES BEING EVALUATED

LIGHTWEIGHT: 1/8 OF CURRENT L.W. GLASS TECHNOLOGY
- DRIVEN BY SINGLE STS LAUNCH
- THIN, HIGH ASPECT RATIOS DRIVEN BY STS VOLUME,
  SHALLOW SHELL BEHAVIOUR

PRODUCIBILITY: SINGLE MOST DEMANDING ISSUE
- UP TO 10.49 1.35 m OFF-AXIS PARABOLAS REQ'D
  AS "FEW" AS 117 4m ONES
- REPLICATION/PRECISION SAGGING/FORMING/.....
- NOVEL APPLICATIONS OF NON-TRADITIONAL MAT'L'S
TASK 1

EVALUATION CRITERIA

SORTING METHODOLOGY

THE EVALUATION CRITERIA

SCORING & TREND ANALYSES

CONCLUSIONS
OVERVIEW OF THIS SECTION

PANEL PARAMETERS TO BE DETERMINED

- SIZE
- SHAPE
- MATERIAL
- STRUCTURAL CONFIG'N

WILL BE EVALUATED AGAINST EVALUATION CRITERIA

- PERFORMANCE CAPABILITY
- COST & SCHEDULE PROJECTIONS
- RISK
- OVERALL SYSTEM/MISSION COMPATIBILITY
# Sorting Methodology

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>CHOICE</th>
<th>IMPORTANCE</th>
<th>ISSUES</th>
<th>RANKING</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1 2 3 4</td>
</tr>
</tbody>
</table>

"EVALUATION CRITERIA!"

\[ \sum \text{IMPORT.} \times \text{RANKING} = \]
SCORING EXPLANATION

WEIGHTING

IMPORTANT OF EVALUATION CRITERIA WITH RESPECT TO:

COST/PREDICIBILITY 10-7
PERFORMANCE 7-3
"DESIGNABILITY" 3-1

RANKING (RAW)

RELATIVE MERIT OF THE TRADE "CHOICE" WITH RESPECT TO THE OTHER CHOICES

10 SUPERIOR
5 "...EHM"
1 WORST

WEIGHTED RANKING

$S_w = \sum \text{IMPORTANCE} \times \text{RAW SCORE}$

- THE HIGHEST VALUE IS THE BEST!
- A "PERFECT" SCORE IS $\sum \text{WEIGHTING FACTOR}$
WEIGHTING FACTORS

GROUND RULES

• COST  
  10 to 7

• PERFORMANCE  
  7 to 3

• PACKAGING INTEGRATION, ENGR'S CONVENIENCE  
  3 to 1
EVALUATION CRITERIA RESULTS

- 1-2 m panels preferable to 4-m panels
- Trapezoids better than hexes
- Thin 'glass' shells & all-aluminum sandwiches have high pay-off potential
- Fused silica/quartz conventional sandwiches technically acceptable w/o risk
- But we believe are cost-wise prohibitive
2. Attractive Panel Possibilities

- Solid "Glass" Monolith
  - Fused quartz (Heraeus)
  - Fused silica (Corning)
  - TGC (Corning or Schott)
  - Pyrex (Corning)

- Metal/Metal Sandwich
  - Alum. "Lighting Sheet" (Alcoa)
  - With foamed Al core (ERG)
HYBRID MIRROR CONCEPT

PERMITS RADIUS OF CURVATURE ADJUSTMENT AS REQ'D TO
ACHIEVE CONGRUENT WAVEFRONT PERFORMANCE

MUTIPLE SUPPORTED PRE-FORMED
"COILZAK" MIRROR SURFACE

ATTACHMENT "GUTTOU"

AXIAL SUPPORT POST

THREAD DIFERENTIAL ASSY

"AJUSTER" NUT

ALUMINUM SHEET
"FOAM"
"SHEET"

BONDED OR BRAZED

CONCEPT ALSO APPLICABLE TO:
GLASS
CE-MC

COMBINATION
MULTIPLY SUPPORTED PLATES

THE BASIS OF HYBRID MIRRORS

INFINITY PLATE
ZERO DEFL.\(\text{W}\)

FINITE PLATE
SMALL DEFLUS DUE TO FINITE EDGE SLOPE
### EVALUATION CRITERIA MATRIX

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>CHOICES</th>
<th>WEIGHTING</th>
<th>EVALUATION CRITERIA</th>
<th>RANKING</th>
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<tbody>
<tr>
<td>SEGMENT SHAPE</td>
<td>a. CIRCLE</td>
<td>3</td>
<td>NO. REQ/DIA</td>
<td>10 5 3 10</td>
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<td>b. HEX</td>
<td>5</td>
<td>OBSCURED AREA</td>
<td>5 9 9 10</td>
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<tr>
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<td>c. TRAPEZOID ✓</td>
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<td>a. 1.35 ✓</td>
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<th>ISOTROPY</th>
<th>MOU-PARITY</th>
<th>VACUUM STABILITY</th>
<th>DIMENSIONAL STABILITY</th>
<th>AVAILABILITY</th>
<th>COST</th>
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<td>10</td>
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</tr>
<tr>
<td>b</td>
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<td>5</td>
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<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
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</tr>
<tr>
<td>c</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
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<td>2</td>
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<tr>
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<td>1</td>
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<td>PARAMETER</td>
<td>CHOICES</td>
<td>WEIGHTING</td>
<td>EVALUATION CRITERIA</td>
<td>a</td>
<td>b</td>
<td>c</td>
<td>d</td>
<td>e</td>
<td>f</td>
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<td>-----------</td>
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</tr>
<tr>
<td>STR'L CONFIG'N</td>
<td>a</td>
<td>THIN SOLID GLAS</td>
<td>✓</td>
<td>9</td>
<td>REPPLICABILITY</td>
<td>7</td>
<td>7</td>
<td>9</td>
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<td></td>
<td>b</td>
<td>SANDWICH GLAS</td>
<td></td>
<td>3</td>
<td>QUILTING</td>
<td>10</td>
<td>1</td>
<td>10</td>
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<tr>
<td></td>
<td>c</td>
<td>THIN SOLID ALUM.</td>
<td></td>
<td>5</td>
<td>DYN. EFFICIENCY</td>
<td>1</td>
<td>8</td>
<td>1</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>d</td>
<td>SANDWICH ALUM ✓</td>
<td></td>
<td>5</td>
<td>CURVATURE STABILITY</td>
<td>10</td>
<td>5</td>
<td>10</td>
<td>5</td>
<td>8</td>
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<td>e</td>
<td>RIBBED</td>
<td></td>
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<td>EDGE CURL</td>
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<td>1</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>f</td>
<td>HYBRID ✓</td>
<td></td>
<td>5</td>
<td>GRAV. RELEASE</td>
<td>8</td>
<td>10</td>
<td>8</td>
<td>10</td>
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<tr>
<td></td>
<td></td>
<td>(✓)</td>
<td></td>
<td>10</td>
<td>COST</td>
<td>2</td>
<td>10</td>
<td>5</td>
<td>1</td>
<td>3</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td>PACKAGING EFFECT.</td>
<td>10</td>
<td>1</td>
<td>10</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td></td>
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<td></td>
<td>263</td>
<td>181</td>
<td>123</td>
<td>226</td>
<td>83</td>
</tr>
</tbody>
</table>
NO. DIFFERENT HEXES TO FILL REFLECTOR DIA.

I.E. TOOLING REQS.
### SEGMENT SHAPE SELECTION

<table>
<thead>
<tr>
<th>CRITERIA</th>
<th>HEX</th>
<th>&quot;SQUARE&quot;</th>
<th>WEDGE</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. req'd for 30 m aper. when D = 4m/ D = 2m</td>
<td>61/271</td>
<td>117/467</td>
<td>32/65</td>
<td></td>
</tr>
<tr>
<td>No. different types req'd</td>
<td>9/30</td>
<td>5/10</td>
<td>2/2</td>
<td></td>
</tr>
<tr>
<td>Max. thickness @ pkg. length</td>
<td>.15/.1m</td>
<td>.08/.08m</td>
<td>.0/.05m</td>
<td></td>
</tr>
<tr>
<td>Normalized allowable at</td>
<td>1/.67</td>
<td>.53/.53</td>
<td>0/.33</td>
<td>(BIG NO. BEST!)</td>
</tr>
<tr>
<td>Productivity assessment</td>
<td>GOOD</td>
<td>GOOD</td>
<td>POOR</td>
<td></td>
</tr>
<tr>
<td>Erectability factor (normalized)</td>
<td>1/4.4</td>
<td>1.9/2.7</td>
<td>.51/1.07</td>
<td>(SMALL NO. BEST!)</td>
</tr>
<tr>
<td>O'ALL PANEL COST ESTIMATE</td>
<td>HIGHER</td>
<td>LOWEST</td>
<td>HIGHEST/RISK</td>
<td>(BASED ON REPUCATION)</td>
</tr>
</tbody>
</table>

Note: The diagram shows the shape selection criteria with respect to hexagonal, square, and wedge shapes.
CURVATURE PRECISION - A CRITICAL PRODUCIBILITY ISSUE

Req'd radius of curvature precision
for

\( \frac{1}{60} \text{ rms coherence WF error} \)

\[
\frac{\Delta R}{R} = \left( \frac{3}{R^2} \right) \Delta W F_{\text{rms}}
\]

Example shown for 5/1
double \( \Delta R/R \) values for 5/2, etc
PANEL SIZE VS PERFORMANCE & MAT'L SELECTION

\[ \Delta W_{F_{\text{rms}}} = \frac{1}{3} \left( \frac{R}{K} \right)^2 \Delta R \]

\[ \Delta R = \frac{R^2 \Delta T'}{h} + R \alpha \Delta T \]

For a solid:
\[ \Delta T' = \frac{Q h}{K} \]
\[ \Delta T = \frac{Q T}{m c_p} \]
\[ \xi m = \rho \]

After manipulation:

\[ D = 2r \leq \frac{Z}{2} \sqrt{\frac{3 \Delta W_{F} R^2}{\left( \frac{R^2}{K} + \frac{R T}{m c_p} \right) \alpha}} \]

RESULTS:
\[ R = 1600^* \]
\[ \Delta W_{F} = 5 \times 10^-3 \]
\[ Q = 0.011 \pm 0.0011 \text{ B/hr in}^2 \]
\[ \tau = 5 \text{ hrs} \]

<table>
<thead>
<tr>
<th>Material</th>
<th>V</th>
<th>w</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alum</td>
<td>98</td>
<td>3/2</td>
</tr>
<tr>
<td>TGC</td>
<td>14</td>
<td>204</td>
</tr>
<tr>
<td>Quartz</td>
<td>134</td>
<td>404</td>
</tr>
<tr>
<td>Pyrex</td>
<td>25</td>
<td>78</td>
</tr>
</tbody>
</table>
The text appears to be discussing the relationship between dynamics and panel size for solids, with a focus on material properties and frequency values.

The equation shown is:
\[ f = \frac{J_a}{2\pi \sqrt{\frac{25EG}{12\pi r^4P^3}}} \]

A table is presented with columns for material (MAT'L), section (SA), 15 Kg/m², 30, 45, t_{solid}, 15 Kg/m², and t_{solid}. The materials listed are aluminum, TGC, quartz, and Pyrex, with corresponding properties. The frequency values (fps) for each material are also provided.
PRE-ASSEMBLED SMALL SEGMENT MODULES
FACILITATES SMALL SEGMENT ERECTABILITY
<table>
<thead>
<tr>
<th>Key Trade Parameters</th>
<th>1-2 m</th>
<th>4 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mat'k Availability</td>
<td>YES</td>
<td>SCALE-UP REQ'D</td>
</tr>
<tr>
<td>Productivity Risk/Panel Cost per ft²</td>
<td>LOWER</td>
<td>HIGHER</td>
</tr>
<tr>
<td>Panel Weight/Specified Frequency</td>
<td>LOWER</td>
<td>HIGHER BY 4X</td>
</tr>
<tr>
<td>Thermal Susceptibility</td>
<td>LOWER</td>
<td>HIGHER BY 4X</td>
</tr>
<tr>
<td>Figure Control Spatial Resolution</td>
<td>BETTER</td>
<td>WORSE</td>
</tr>
<tr>
<td>Actuators &amp; Controls</td>
<td>HIGHER COST</td>
<td>LOWER COST</td>
</tr>
</tbody>
</table>

**Better individual panel performance & cost effectiveness traded off against actuator & control costs: Smaller panels recommended.**
ANOTHER EXAMPLE OF WHERE SEVERAL SMALL ONES WERE SUPERIOR TO A GIANT SCALE-UP!

....'NUFF SAID
MATERIAL & MECHANICAL CONFIGURATION
$$E/\rho^3, \text{ A DYNAMICS PARAMETER}$$

$$S = \frac{1}{2\pi} \sqrt{\frac{2SEIg}{WR^2}}$$

$I = \frac{t^3}{12} \left( \text{in}^3 \right)$
$g = 386 \text{ in/sec}^2$
$W = \text{Segment weight (lbs)}$
$E = \text{Modulus of Elasticity (lb/\text{in}^2)}$
$R = \text{Segment radius (in)}$

$W = p_A \pi R^2 \quad \text{where } p_A \text{ is AREAL DENSITY (lb/\text{in}^2)}$

$I = \frac{t^3}{12}$

$$S = \frac{1}{2\pi} \sqrt{\frac{2SEt^3g}{12 p_A \pi R^4}}$$

Also $p_A = p t$ for solid minors or $t^3 = \frac{p_A^3}{\rho^3}$

$$S = \frac{1}{2\pi} \sqrt{\frac{2S E p_A^3 g}{12 p_A \pi R^4 \rho^3}}$$
SOLID/SANDWICH THERMAL TRADE SUMMARY

\[ \Delta T = \frac{Q}{K} \left[ 2t \left( 1 - \frac{1}{N} \right) + \frac{h}{N} \right] \]

\[ K = 8.33 \text{ B/hr in } F^\circ \text{ (alum.)} \]
\[ t = 0.05 \]
\[ N = 0.07 \text{ (12 lb/ft}^3 \text{ core)} \]

<table>
<thead>
<tr>
<th>h</th>
<th>( \Delta T / h )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0171 ( ^\circ F/\text{hr} )</td>
</tr>
<tr>
<td>2</td>
<td>0.0180</td>
</tr>
<tr>
<td>3</td>
<td>0.0193</td>
</tr>
<tr>
<td>4</td>
<td>0.0184</td>
</tr>
<tr>
<td>0 (solid)</td>
<td>0.0013</td>
</tr>
</tbody>
</table>

\[ \Delta R = R^2 \kappa \left( \frac{\Delta T}{h} \right) \]

STABLE STATE MODEL

SOLIDS ARE THERMALLY MORE STABLE

ALUM EXAMPLE SHOWN, SIMILAR CONCLUSIONS FOR "GLASSES"
THERMAL ANALYSIS RESULTS SUMMARY*

for

STATIC AXIAL GRADIENT ASSESSMENT

\( d \ll D \quad \therefore \text{NO LATERAL GRADIENTS IN SEGMENT} \)

\[ Q = 0.011 + 0.0011 \]

\[ d \]

\[ Q = 0.011 - 0.0011 \text{ B/hr in}^2 \]

\[ L = \frac{1}{2} D \]

*DETAILS IN THERMAL ANALYSIS SECTION*
FUSED SILICA/QUARTZ SANDWICH

2.4 m CONVENTIONAL MIRRORS "OK"

\[ T = 100 \text{ K} \]

CTE @ 200 °K
CORNING FUSED SILICA \( 0.16 \times 10^{-6} \text{ in/in/°F} \)
HERAEUS QUARTZ \( 0.08 \times 10^{-6} \)

\( K \) (Conductivity) \( 0.067 \text{ B/hr in °F} \)

\[ \Delta T = \frac{Q}{K} \left( 2 \pi (1 - \frac{1}{n}) + \frac{n}{N} \right) \]

(Neglecting radiation heat x-fbr)

\[ \Delta T/k = 0.17 \text{ °F/in when } \Delta Q = 0.011 \text{ B/hr in}^2 \]
(10% side-to-side flux variation)

\[ \Delta R/R = R \Delta T \]

\( k \) for \( R = 1200" \) (i.e. 15 m S/F):

- CORNING \( \Delta R/R = 0.000033 \)
- HERAEUS \( \Delta R/R = 0.000016 \)

\( \text{OK for 2.4 m segments} \)
**FUSED SILICA/QUARTZ SOLIDS**

\[ \rho_A = 139 \text{ Kg/m}^2 \]

\[ \frac{\Delta T}{h} = \frac{Q}{K} = \frac{0.0011}{0.067} = 0.016 \text{ °F/w} \quad (10 \times \text{better than s'wich!}) \]

\[ \frac{\Delta R}{R} = 1200 \times 1.16 \times 10^{-6} \times 0.016 = 3.1 \times 10^{-6} \]
OF POOR QUALITY

ORIGINAL PAGE IS
OF POOR QUALITY

ALUMINUM SANDWICH (STEADY STATE GRADIENT)

K = 8.84/hr in

\[ \Delta R = 1200 \times 12 \times 10^{-6} \times 0.019 = 0.000027 \]

\[ \Delta T = \frac{0.019}{h} \text{ °F/in} \]

N = 0.17

UP TO 80" (2-m) PAVELS OK!
SHELL DYNAMIC CHARACTERISTICS
APPROXIMATE RELATIONSHIPS
FOR "GLASS" TYPE PANELS

\[ d = \text{PANEL SIZE} \]

**Graph:**
- First mode (CPs) vs. shell thickness (in)
  - \( d = 60" \) (1.5 m)
  - \( d = 40" \) (1 m)
  - \( d = 80" \) (2 m)

**Legend:**
- SHELL THICKNESS (in)
CONCLUSIONS

- SMALL PANELS
  - LESS COSTLY
  - LESS TECHNICAL RISK
  - MORE ACCURATE

TRAPEZOIDAL SHAPE

- FAVORS REPLICATION
- BETTER STREHL

TRANSPARENT GLASSY CERAMICS OR ALUMINUM

- EXPLOITATION OF "COMMON" MATERIALS
- BOTH ARE "REPLICABLE"
- GOOD CANDIDATES FOR DEVELOPMENT PROGRAM

SOLIDS (GLASS) & SANDWICHES (ALUMINUM)

- COMATIBLES WITH "SMALL" REPLICABLE MATERIALS
- SELECTED MATERIAL CHARACTERISTICS
TASK 2
CURRENT TECHNOLOGY ASSESSMENT
POTENTIAL SUPPLIER CONTACTS

PHONE CONTACT

FOLLOW-UP LETTER

PHONE CALLS/ VISITS/ DIALOGUE

CORNING HERAEUS SCHOTT COORS METCO BATTelle ALCOA EFG PE UNION RES. CARBIDE

FUSED SILICA TEC PUREX FUSED QUARTZ TEC-BEBBOP* PRECISION FORMED CERAMICS FLAME SPRAY REPLICATION SO-CEL REFINED BRIETE-FINISHED ALUMINUM ROUGHED ALUMINUM HIP BERYLLIUM HIP CERAMICS FLAME SPRAYED CERAMICS GRAINITE-MAGNESIUM HYBRID CONCEPT

* DARPA TECHNOLOGY @ PE
CORNING

- TRANSPARENT GLASS CERAMIC # 9618

- $E = 11.2 \times 10^6 \text{ lb/in}^2$
- $\rho = 0.09 \text{ lb/in}^3$
- $\alpha = 0.013 \times 10^{-6} \text{ in/in/°F} \quad (0-300^\circ \text{C})$

CTE IS TAILORABLE TO FAVOR 200°K OPERATING TEMP

- SAGGABLE & CAN BE VACUUM FORMED
- DIE FORMING w/GRAPHITE OR SiO2 FORMS TO BE INVESTIGATED

- BASICALLY AN INEXPENSIVE MATL, ITS USED FOR RANGE-TOPS!
HERAEUS

"OPTASIL" FUSED QUARTZ

HAS BEEN PRECISION FORMED BETWEEN GRAPHITE DIES

25,000 \AA\ SMOOTHNESS

COULD BE POLISHED TO 2000-3000 \AA\ LOR REFT

COST IS $13,300 FOR A 1-m SHELL IN QUANTITIES OF 1000.

COULD BE PRODUCED 2/2 PER WEEK

O'ALL SHAPE ERROR \leq 10 \mu m TO BE VERIFIED
METCO (A DIVISION OF PE)

- A HIGH RISK/HIGH PAYOFF APPROACH
- FLAME SPRAYED CERAMIC OR FUSED QUARTZ
- CURRENTLY AN IR&D PROPOSAL FOR FY '83
REPLICATED LIGHTWEIGHT MIRROR CONCEPT

CERAMIC BACK PLATE (OPTIONAL)

CONSOLIDATED OUTER SURFACE ON FOAMED REINFORCEMENT

PLASMA SPRAYED CERAMIC REFLECTOR

DIA:METER \( 40 \leq D \leq 60 \) inches

RADIUS OF CURVATURE \( 300 < R < 2400 \) inches

TOLERANCE \( 300 \pm 0.025 \) \( 2400 \pm 0.132 \) inches

OVERALL SURFACE ACCURACY \( 15 \times 10^{-6} \) inches RMS

SMOOTHNESS \( 4 \times 10^{-6} \) inches RMS

QUANTITY READY UP TO 1000

REPRESENTATIVE PARAMETERS
ALCOA/ERG

- Ultra-smooth aluminum lighting sheet COILZAK (R)
- Foamed aluminum core mat'ls.

Smoothness: 1000 ± 500 Å rms
Reflectivity: Good w/gold overcoat

Holds promise for very inexpensive panels in the 1 to 1½ m size range

"Stamped" reflector (COILZAK)

[Diagram: All-aluminum mechanically replicated panel; no figuring or polishing req'd (more info. in subs. section)]
SUCCESS CRITERIA for ALUMINUM SANDWICHES

\[ \Delta W F_{\text{rms}} = \frac{1}{60} = 0.5 \mu \text{ BUDGET} \]

\[ \Delta W F_{\text{rms}} = \frac{1}{2} \Delta p - p \quad (\text{from} \quad \Delta W F = \frac{1}{3} (\xi)^2 \Delta R) \]

\[ \therefore \Delta p - p \approx 40 \times 10^{-6} \text{ in} \quad (\text{i.e.} \quad 1 \mu) \]

IF ALL SEGMENTS WITHIN A 20°F RANGE

\[ \Delta p - p / ^\circ F = 2 \times 10^{-6} \]
\[ M = \frac{P_0}{t_{i+1} + t_{i+2}} \left\{ \frac{1}{\frac{1}{E_{t_{i+1}}} + \frac{1}{E_{t_{i+2}}}} \right\} \Delta T \]

After solving for \( P_i \) and \( P_{i+1} \):

\[ M = \frac{(d_e - d_i)(t_{i+1} + t_{i+2})}{2} \]

\[ \Delta T = \frac{M r^2}{2 E I} \]

And:

\[ \Delta T = \frac{M r^2}{2 E I} \]
**THERMAL BENDING SENSITIVITY**

**ALL-ALUM SANDWICH, \( \Delta t_2 = t_2 \)**

Original print is of poor quality.

<table>
<thead>
<tr>
<th>( h )</th>
<th>( t_2 )</th>
<th>SEGMENT DIA</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta t_2 )</td>
<td>( \Delta t_2 )</td>
<td></td>
</tr>
<tr>
<td>( 0.5 ) in.</td>
<td>( 0.004 ) in.</td>
<td>( 4.9 \times 10^{-6} )</td>
</tr>
<tr>
<td>( 0.006 )</td>
<td>2.16</td>
<td>8.6</td>
</tr>
<tr>
<td>( 0.008 )</td>
<td>10.4</td>
<td>41.6</td>
</tr>
<tr>
<td>( 0.75 )</td>
<td>( 0.004 )</td>
<td>( 2.16 )</td>
</tr>
<tr>
<td>( 0.006 )</td>
<td>2.0</td>
<td>13.4</td>
</tr>
<tr>
<td>( 0.008 )</td>
<td>4.6</td>
<td>18.4</td>
</tr>
<tr>
<td>( 1 )</td>
<td>( 0.004 )</td>
<td>1.21</td>
</tr>
<tr>
<td>( 0.006 )</td>
<td>1.21</td>
<td>7.6</td>
</tr>
<tr>
<td>( 0.008 )</td>
<td>2.61</td>
<td>10.4</td>
</tr>
<tr>
<td>( 1.25 )</td>
<td>( 0.004 )</td>
<td>0.8</td>
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<tr>
<td>( 0.006 )</td>
<td>1.21</td>
<td>4.84</td>
</tr>
<tr>
<td>( 0.008 )</td>
<td>1.67</td>
<td>15.</td>
</tr>
<tr>
<td>( 1.5 )</td>
<td>( 0.004 )</td>
<td>0.54</td>
</tr>
<tr>
<td>( 0.006 )</td>
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<td>( 0.008 )</td>
<td>1.16</td>
<td>4.16</td>
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<td>0.3</td>
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<tr>
<td>( 0.006 )</td>
<td>1.47</td>
<td>1.9</td>
</tr>
<tr>
<td>( 0.008 )</td>
<td>1.65</td>
<td>2.6</td>
</tr>
</tbody>
</table>

\[ \frac{\Delta \rho}{\rho} / \text{inches} \]

Acceptable region: \( \frac{\Delta \rho}{\rho} / \text{inches} < 2 \) in \( \text{inches} / \text{degree F} \)

Page 51
COMPARISON WITH GR-EP/AL. HONEYCOMB PANEL

- COMPOSITE PANEL

\[ M = \frac{h^2(d_2 - d_1) t_1 E_1}{2 R (1 - \nu)} \]

\[
\begin{align*}
 h &= 1.5 \\
 t_1 &= 0.4 \\
 E_1 &= 15 \times 10^6 \\
 R &= 1600 \\
 \Delta x &= 12 \times 10^{-6}
\end{align*}
\]

\[ M = 0.0051 \text{ in.-lb/in./}^2 \text{F} \]

- FOR \( h = 1.5 \) \( \xi \) \( t_1 = 0.04 \) \( \xi \) \( t_2 + \Delta t_2 = 2 t_2 \) ALL ALUM. MIRROR

\[ M = 0.0012 \text{ in.-lb/in./}^2 \text{F} \]

INDUCED BENDING MOMENT LESS IN ALL-ALUM MIRROR!
TASK 3

IDENTIFY & EVALUATE PRIME TECHNOLOGIES
**Why We Selected the Aluminum Sandwich for the Experiment**

**Candidate LDR-Type Mirrors**

<table>
<thead>
<tr>
<th>Candidate</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed silica, fixed quartz sandwiches</td>
<td>Too expensive for LDR but it would definitely work</td>
</tr>
<tr>
<td>Fused silica, fused quartz thin solids</td>
<td>(Semi-) replicable but very expensive and very long lead times</td>
</tr>
<tr>
<td>Lithium alum. silicate thin solids</td>
<td>Immune to Corning (smooth data), a definite maybe!</td>
</tr>
<tr>
<td>Pyrex thin solid</td>
<td>CTE's too high, k's too low, but its cheap &amp; replicable</td>
</tr>
<tr>
<td>COILZAK alum sandwich</td>
<td>We think it's replicable &amp; stable enough &amp; cheap!!!</td>
</tr>
<tr>
<td>COILZAK multiply impregnated on gr-mg</td>
<td>Too dependent on development of stable graphite-magnesium</td>
</tr>
<tr>
<td>Machined &quot;aluminum&quot; casting</td>
<td>Too expensive vis à vis figuring labor</td>
</tr>
<tr>
<td>Gr-ep sandwich (al. or novex core)</td>
<td>COILZAK AL-AL SANDWICH IS LESS THERMALLY SENSITIVE!</td>
</tr>
<tr>
<td>HIP beryllium</td>
<td>Too expensive for LDR but it would work</td>
</tr>
<tr>
<td>Metco flame sprayed XXX replicas</td>
<td>A long shot, may have big payoff, embryonic stage</td>
</tr>
</tbody>
</table>

* Fresenitus Alcoa alum lighting sheet, 1000 A smoothness |
* CORNINGWARE precursor glassy ceramic
COST ESTIMATE EXAMPLE
DIRECT COSTS, NO FEE, etc.!!!

WAG ONLY

HERAEUS 1-m PANELS

<table>
<thead>
<tr>
<th>QUANTITY</th>
<th>COST EACH</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$95,500</td>
</tr>
<tr>
<td>7</td>
<td>38,800</td>
</tr>
<tr>
<td>1000</td>
<td>13,300</td>
</tr>
</tbody>
</table>

ASSUME 23,000 IN THE 250-750 QUANTITY RANGE

DELIVERY RATE: 2 per WEEK

<table>
<thead>
<tr>
<th>SHAPE</th>
<th>REFLECTOR DIA. (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>15</td>
</tr>
<tr>
<td>TRAPEZOID</td>
<td>353</td>
</tr>
<tr>
<td>HEX</td>
<td>221</td>
</tr>
</tbody>
</table>

NO. PANELS REQ'D
CUT FROM 1-m CIRCULAR BLANK
### Cost Estimate (cont'd) WAG only

<table>
<thead>
<tr>
<th>PROCUREMENT CYCLE</th>
<th>NO. 1-m PANELS DEL.</th>
<th>COST*</th>
<th>REFLECTOR SIZE</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 yrs</td>
<td>312</td>
<td>$8.4 \times 10^6</td>
<td>16.1 m, 16.1 m</td>
</tr>
<tr>
<td>5 yrs</td>
<td>520</td>
<td>$13.9 \times 10^6</td>
<td>18.2, 21</td>
</tr>
<tr>
<td>7 yrs</td>
<td>728</td>
<td>$6 \times 10^6</td>
<td>21.5, 24.6</td>
</tr>
<tr>
<td>9 yrs</td>
<td>936</td>
<td>$16.9 \times 10^6</td>
<td>29</td>
</tr>
</tbody>
</table>

*INCL. 120 hrs/panel to SMOOTH FROM 25,000 to 2000 Å*
"Class" procurement preliminary example using Heraeus data

WAG only

Reflector dia (in.)

Power costs (millions of $/yr)
ACTUATOR COSTS & PANEL SIZE TRADE

No. Blanks Req'd \( N \approx \left( \frac{D}{d} \right)^2 \)  
\( D = \text{REFL. DIA} \)  
\( d = \text{PANEL DIA} \)

No. Actuators Per Panel = 6

Reflector Cost \( \approx \left( \frac{D}{d} \right)^2 \left[ B + 6A \right] \)  
\( B = \text{Blank Cost} \)  
\( A = \text{Actuator Cost} \)

4m  \( B \approx 2.5 \times 10^4 \)  FUSED SILICA S'WICH  
2m  \( B \approx .7 \times 10^6 \)  " " "  
1m  \( B = 13,300 \)  FUSED QTZ SHELL

ACTUATOR "BREAK-EVEN" COSTS

$25,000 \rightarrow 36,000 \text{ each}

I think they will cost less!! Probably much less!!

\( \sim \) SMALLER PANELS WILL BE MORE COST EFFECTIVE \( \sim \)
TO BE DONE

- DEFINE ACTUATOR REQS
- ESTIMATE ACTUATOR COSTS
  DEVELOPMENT THRU GUAL
  RECURRING
- CONFIRM BREAK-EVEN POINT CONCLUSIONS
### Recommended Candidates for Continued Development

**2/25/82**

<table>
<thead>
<tr>
<th>Recommended for Further Investigation &amp; Development</th>
<th>Technology Already Exists, and/or is Being Pursued</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum Switch Hybrid</td>
<td>TGC</td>
</tr>
</tbody>
</table>

- **Joining Mater**: Filled Epoxy, Gallium-Alum
- **Forming Accuracy**: Molding Processes
- **Molding Techniques**: Molding Work, Smoothing Techniques
- **Potential Cost & Delivery Improvement**: Fritted Core Concepts
UP TO THIS POINT:

THERMAL DEFORMATION & DYNAMIC ANALYSES

PREDICATED ON FLAT-PLATE THEORY.

THIS IS CONSERVATIVE!

NEXT SPEAKER WILL ADDRESS:

EFFECTS OF INITIAL CURVATURE
i.e. SHALLOW SHELL THEORY
BENDING & EXTENSIONAL STRAINS
WHICH STIFFEN THE SEGMENTS.
LARGE DEPLOYABLE REFLECTOR

SEGMENT TECHNOLOGY ASSESSMENT STUDY

TASK 4: ANALYTIC STUDIES & PERFORMANCE PREDICTIONS

- STRUCTURAL/MECHANICAL TREND AND

SENSITIVITY STUDIES - G. RUT IVEN
STRUCTURAL/MECHANICAL TREND STUDIES

- MODEL DEVELOPMENT AND CORRELATION
- F/NO (I.E., INITIAL CURVATURE) STIFFENING EFFECTS
- STATICALLY DETERMINATE & MULTIPLY SUPPORTED PLATES
- ΔR/R PERFORMANCE PREDICTIONS

G.P.R. - 2/25/82
ANALYSIS METHODS

- ALL ANALYSIS UTILIZED THE GENERAL PURPOSE FINITE ELEMENT COMPUTER PROGRAM,

MSC/NASTRAN

MODEL CONSTRUCTION

- UTILIZATION OF CTRIA3 & CQUAD4 ISOPARAMETRIC PLATE ELEMENTS

MODEL VERIFICATION

- INITIAL NASTRAN MODEL (BASELINE MODEL) VERIFICATION ACCOMPLISHED

"CLOSED-FORM SOLUTION" CORRELATION.

- HIGHER ORDER ANALYSIS EMPLOYED "BASELINE MODEL" MODIFIED FOR INVESTIGATION

OF SEVERAL PARAMETER CHANGES (i.e., BOUNDARY CONDITIONS, F/N0's, ETC.)

- THIS MODIFICATION ENTAIRED MESH REFINEMENT OF THE (+) (+) SEGMENT QUADRANT
<table>
<thead>
<tr>
<th>MODEL NAME*</th>
<th>NO. OF NODES</th>
<th>NO. OF ELEMENTS</th>
<th>NO. OF D.O.F.</th>
</tr>
</thead>
<tbody>
<tr>
<td>4M-4 NODE</td>
<td>81</td>
<td>64</td>
<td>486</td>
</tr>
<tr>
<td>4M-6 NODE (BASELINE MODEL)</td>
<td>169</td>
<td>144</td>
<td>1014</td>
</tr>
<tr>
<td>4M-12 NODE</td>
<td>289</td>
<td>276</td>
<td>1734</td>
</tr>
<tr>
<td>4M-24 NODE</td>
<td>433</td>
<td>564</td>
<td>2598</td>
</tr>
<tr>
<td>2M-12 NODE</td>
<td>79</td>
<td>75</td>
<td>474</td>
</tr>
</tbody>
</table>

*THE SIGNIFICANCE OF -4NODE, -6NODE, -12NODE, ETC. IS THAT THESE DESCRIBE THE NUMBER OF ELEMENTS ALONG THE DIAGONAL OF THE REFINED MESH QUADRANT.*

G.P.R. - 2/25/82
4M-12NODE LDR MODEL PLOTS

- 289 NODES
- 276 ELEMENTS
- 1734 D.O.F.

*NODE/ELEMENT CONNECTIVITY*

*ELEMENT "SHRINK" OPTION*

SKewed plot to show initial radius of curvature

G.P.R. - 2/25/82
# Model Verification Results

- All correlations used the "baseline model"

<table>
<thead>
<tr>
<th>Model Configuration</th>
<th>Boundary Condition</th>
<th>Load Condition</th>
<th>% Discrepancy from Closed-Form Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat Plate</td>
<td>Center node constrained (statically determinate)</td>
<td>Thru-the-thickness thermal gradient</td>
<td>0.00</td>
</tr>
<tr>
<td>Flat Plate</td>
<td>Clamped-clamped</td>
<td>Point load at center node</td>
<td>0.80</td>
</tr>
<tr>
<td>Shallow Shell (f/7.5)</td>
<td>Multiply supported</td>
<td>Thru-the-thickness thermal gradient</td>
<td>0.00</td>
</tr>
</tbody>
</table>

G.P.R. - 2/25/82
MODEL VERIFICATION PLOTS
(LATERAL* DIRECTION DISPLACEMENTS)

- CLAMPED-CLAMPED FLAT PLATE
  POINT LOAD @ CENTER

- STATICALLY DETERMINATE FLAT PLATE
  TRANSVERSE THERMAL GRADIENT

\( \delta_{\text{MAX}} = 2.45 \text{ INCHES} \)

*LATERAL, IN ALL PROCEEDING VIEWGRAPHS, IS SYNONYMOUS WITH AXIAL

\( \delta_{\text{MAX}} = 2.87 \times 10^{-4} \text{ INCHES} \)

G.P.R. - 2/25/82
### Applicable Segment f/No's

#### Segment f/No

<table>
<thead>
<tr>
<th>Segment Dia. (Meters)</th>
<th>Aperture (Meters)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30M</td>
</tr>
<tr>
<td></td>
<td>f/1.0  f/.5</td>
</tr>
<tr>
<td>4M</td>
<td>7.5    3.75</td>
</tr>
<tr>
<td>2M</td>
<td>15.0   7.5</td>
</tr>
<tr>
<td>1M</td>
<td>30.0   15.0</td>
</tr>
</tbody>
</table>

\[ R_C = 60M \quad R_C = 30M \quad R_C = 40M \quad R_C = 20M \quad R_C = 30M \quad R_C = 15M \]

**Note:** \( R_C \) = Radius of Curvature

G.P.R. - 2/25/82
PANEL STUDIES

• SYSTEM/SEGMENT F/NO'S (DETERMINATION OF BEHAVIOR REGIME)
  - FLAT PLATE VS. SHALLOW SHELL BEHAVIOR

• BOUNDARY CONDITIONS
  - STATICALLY DETERMINATE
  - MULTIPLY SUPPORTED

• SEGMENT SIZE

• MATERIAL SELECTION
  - LINEAR EXTRAPOLATION EQUATION

\[ \Delta T \times E \times a \times (6) \]

• SEGMENT THICKNESS

G.P.R. - 2/25/82
4/4 FOR SEGMENT

LATERAL DISPLACEMENTS [GRADIENT=3.0/1]
BOUNDARY CONDITIONS

- A Design Consideration (for radius of curvature adjustment):

  Post supported (in the lateral direction) infinite plates do not bend (excluding edge effect propagation) due to thru-the-thickness thermal gradient.

- Boundary Conditions Investigated (2M & 4M Segments)

  1) Statically Determinate System (Rigid Body Constraints)

  2) Post Supported Segment w/o Edge Supports

  3) Post Supported Segment with Edge Supports

G.P.R. - 2/25/82
SEGMENT THICKNESS VARIATIONS

• SENSITIVITY OF THICKNESS ON STIFFNESS
OF POOR QUALITY
$$R_c = \frac{r^2}{2A}$$

$$\frac{dR}{d\Delta} = \frac{r^2}{2A}$$

$$\Delta R = \frac{1}{2} \rho \left( \frac{r}{h} \right)^2 d\Delta$$

$$\Delta R = \frac{1}{2} \rho \left( \frac{r}{h} \right)^2 d\Delta$$

**AR CALCULATIONS**

"FREE PLATE" + STATICALLY DETERMINATE

1.5M, 2M, & 4M LDR SEGMENT

$$\Delta T = 3.09^\circ F/IN, \ a = 0.03 \times 10^{-6} \ IN/^\circ F$$

$$R_c = 2362 \ IN \ (THK = 0.3241 \ IN)$$

<table>
<thead>
<tr>
<th>$\frac{AR}{\rho} = \frac{1}{2} \frac{R}{R^2} d\Delta$</th>
<th>INITIAL CURVATURE Y-COORDINATE ($\Delta_y$)</th>
<th>DEFLECTION ($\Delta\alpha$)</th>
<th>$\Delta R = \frac{-1}{2\Delta_y^2} d\Delta$</th>
<th>$\Delta R/R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Theta$</td>
<td>29.53</td>
<td>.1846</td>
<td>$4.44 \times 10^{-5}$</td>
<td>$0.000677$</td>
</tr>
<tr>
<td></td>
<td>39.37</td>
<td>.3279</td>
<td>$1.78 \times 10^{-4}$</td>
<td>$-1.5994$</td>
</tr>
<tr>
<td></td>
<td>78.74</td>
<td>1.3128</td>
<td>$9.487 \times 10^{-5}$</td>
<td>$-0.1706$</td>
</tr>
</tbody>
</table>

$$\Delta = \frac{r^2 \Delta \alpha}{2h} = \frac{4 \times 0.03 \times 10^{-6} \times 0.3241}{2} = 4.04 \times 10^{-5}$$

G.P.R. _ 2/25/82
TREND STUDY APPLICATION

- ALL SENSITIVITY STUDIES WERE BASED ON 3.09°F/IN

\[ \frac{\Delta T}{h} = \frac{Q}{k} \]  \( k = \text{THERMAL CONDUCTIVITY} \)

\( Q \) = 0.011 BTU/HR.IN²

\( k \) = 0.07 BTU/HR.IN.°F

\( k \) = 8.00 BTU/HR.IN.°F

\[ \frac{\Delta T}{h} = \frac{0.011}{0.07} = 0.16 \text{ °F/IN} \]  + \[ \frac{3.09\text{°F/IN}}{0.16\text{°F/IN}} = 19.31 \]

\[ \frac{\Delta T}{H} = \frac{0.011}{8.00} = 0.0014 \text{ °F/IN} \]  + \[ \frac{3.09\text{°F/IN}}{0.0014\text{°F/IN}} = 2207.14 \]

REDUCTION FACTORS TO BE APPLIED TO SENSITIVITY DISPLACEMENT DATA

G.P.R. - 2/25/82
CURVATURE PRECISION
A CRITICAL PRODUCIBILITY ISSUE

REQUIRED RADIUS OF CURVATURE PRECISION
for
\( \frac{1}{60} \text{ rms coherence WF Error} \)

\[
\frac{\Delta R}{R} = \left( \frac{3}{R^2} \right) \Delta W F_{\text{rms}}
\]

Example shown for 5/1
double \( \frac{\Delta R}{R} \) values for \( \frac{1}{2} \), etc.

\[
\begin{align*}
\frac{\Delta R}{R}_{\text{model}} &= \left( \frac{4}{R^2} \right) \left( \frac{\text{factor}}{1} \right) \left( \frac{\text{factor}}{1} \right) \\
&= \frac{0.00577 \times 0.08 \times 10^{-3} \text{ in/ft} \times \frac{1}{1231}}{0.05 \times 10^{-3} \text{ in/ft} \times 1} = 0.000393
\end{align*}
\]

like \( \theta \) 134° on pg. 15

SEGMENT DIAMETER (INCHES)
CONCLUSIONS

- MODELS WORKING PROPERLY AND READY FOR DETAILED STUDY OF SELECTED CANDIDATES.

- SHELL CHARACTERISTICS SHOW STIFFENING EFFECT
  - MAKES FLAT PLATE EVALUATION CRITERIA RESULTS CONSERVATIVE

- ΔR/R THERMAL EFFECT WITHIN SPEC. FOR THIN "GLASS" SHELLS

G.P.R. - 2/25/82
THERMAL ANALYSIS

OBJECTIVE

INVESTIGATE THERMAL STABILITY OF LDR MIRROR SEGMENTS

- MINIMIZE ENVIRONMENT CHANGES
- MAINTAIN MIRROR SURFACE AT LOW TEMPERATURES PASSIVELY

METHOD

DETERMINE PASSIVE ENCLOSURE DESIGN

ANALYZE MIRROR SEGMENTS

STATUS

- ENCLOSURE DESIGN CONCEPT COMPLETE
- SEGMENT THERMAL MODEL OPERATIONAL
- SEGMENT THERMAL ANALYSIS UNDERWAY

R.G.B. 2/23/82
ANALYSIS PLAN

- DETERMINE "REALISTIC" THERMAL ENVIRONMENTS
  - MINIMIZE HEAT LOADS
  - MINIMIZE SIDE TO SIDE GRADIENTS
  - LOW TEMPERATURES

- DEVELOP SEGMENT THERMAL MODEL
  - ANALYZE MIRROR SEGMENTS UNDER "BEST" THERMAL CONDITIONS

- RESULT: INTEGRATED DESIGN
  - THERMAL STABILITY IS A FUNCTION OF ENVIRONMENT

R.G.B. - 2/23/82
LDR ENCLOSURE DESIGN PARAMETERS

PARAMETER

FWD ENCLOSURE LENGTH (L)  CONTROLS ENERGY IRRADIATING/ABSORBED BY LDR
ENCLOSURE MLI  MINIMIZES SIDE TO SIDE GRADIENTS WITH MLI MAX = .40°F
WITHOUT MAX = 460°F
RADIATOR  PROVIDES AN AREA FOR EARTH IR AND ALBEDO ENERGY REJECTION
RADIATOR/SHADE
SUN SHADE  ELIMINATES POSSIBILITY OF THE SUN IRRADIATING THE
INTERIOR OF THE FORWARD ENCLOSURE.

MATERIAL
ABSORBIVITY (α)  THERMAL RADIATION PARAMETERS
EMISSIVITY (ε)

TYPICAL VALUES EXTERNAL ENCLOSURE α/ε = .2/.8
LDR α/ε = .1/.1, INTERNAL ENCLOSURE α/ε = .8/.8
LDR MAXIMUM ENERGY ABSORBED BY REFLECTOR

EQUATIONAL ORBIT PARAMETERS
ALTITUDE - 400 MILES
IRRADIATING ENERGY
SOLAR 457 BTU/HR FT^2
EARTH IR 87 BTU/HR FT^2
EARTH ALBEDO 192 BTU/HR FT^2

EQUATION FOR QUALITY

R.G.B. - 2/23/82
LDR INTERNAL VIEW TO SPACECRAFT

F (1) + (2)

R WHERE L = RD

R.G.B. - 2/23/82
SEGMENT THERMAL MODEL

- TRANSIENT SINDA MODEL
- USER DEFINES
  - MATERIAL
  - THICKNESS
  - EMISSIVITY
  - CONDUCTIVITY
FOR THE FORWARD FACEPLATE, MID-SECTION, AFT FACEPLATE INDEPENDENTLY.
- USER DEFINES FORWARD & AFT FACEPLATE ENVIRONMENTS
- RESULTS NA STRAN COMPATIBLE

FORWARD FACEPLATE

ONE NODE
CONDUCTION ONLY

MID-SECTION

FOUR NODES
RADIATION & CONDUCTION

AFT FACEPLATE

ONE NODE
CONDUCTION ONLY

R.G.B. - 2/23/82
CONCLUSIONS

- Space Craft L/D major driver in environment

- Low temperatures are achievable

- Now on to segment analysis

R.G.B. - 2/23/82
LDR
SEGMENT TECHNOLOGY ASSESSMENT
STUDY

FINAL BRIEFING
LDR
SEGMENT TECHNOLOGY ASSESSMENT

FINAL BRIEFING

9/21/82

PERKIN-ELMER
TOP LEVEL LDR REQUIREMENTS

(From SOW & Attachments)

OVERALL DIA.............. 10 ≤ D ≤ 30 m

FIGURE TYPE............. PARABOLA OR HYPERBOLA/NOT SIMPLY SPHERICAL

FIGURE QUALITY.......... D/L ≤ 30 μ = \frac{λ}{13.7} \text{ RMS OR } 2.2 \text{ μ} \text{ MIRROR SYSTEM RMS}

SPEED...................... F/0.5 TO F/1

WEIGHT..................... 25000 LBS (11360Kg) INCL ACTUATORS

OPERATING TEMP........... 150 - 200°K (-100 TO -190°F)

OPERATING W/L............. 2 μ TO 1000 μ

DYNAMICS.................. 0.00035g (SLEW), F > 10 cps (SPATIAL CHOPPING)

STABILITY.................. PASSIVE SEGMENTS PREFERRED

TECHNOLOGY DEMO.......... 1987

OPERATIONAL SYS.......... 1993

DEPLOYMENT............... SINGLE STS FLIGHT, MANUAL ASSIST OK

MISSION DURATION.......... 10 YRS — surface/dimension change

10/15/81 HK
PANEL REQUIREMENTS

PERFORMANCE

.25 μ RMS FIGURE
125 x 10^-6 AR/R
200° K OPERATION
10 Kg/m^2 @ Δθ' 1.5m
ALL OFF-AXIS PARABOLAS

PROGRAMMATICS

UP TO 500 PANELS REQ'D
TWO PER WEEK SCHEDULE GOAL
(5 yr TARGET)
1987 TECHNOLOGY READINESS
"AFFORDABLE" COSTS

CONCEPT DEVELOPMENT & EVALUATION

SELECTION (S)

TECHNOLOGY DEVELOPMENT PLAN

SCOPE OF THE CURRENT LDR PROGRAM
THE LDR PROGRAM IN A NUTSHELL
LDR SEGMENT TECHNOLOGY ASSESSMENT STUDY

THE SOW TASKS

. REQUIREMENTS & EVALUATION CRITERIA
. ASSESS EXISTING TECHNOLOGY
. IDENTIFY & EVALUATE PRIME TECHNOLOGIES
. ANALYTIC STUDIES & PERFORMANCE PREDICTIONS
. DESIGN DEFINITION & CONCEPT SELECTION
. TECHNOLOGY DEVELOPMENT PLANS FOR TWO MOST PROMISING CONCEPTS
CONCLUSIONS

- FUSED QUARTZ SANDWICH PANELS
  - 15 kg/m²
  - 1.5-2 m DIAMETER SEMI-REPLICATION
  - UNIQUE MANUFACTURING IDEAS
- ALTERNATE MATERIAL EXPERIMENTS
  - ADDITIONAL (DOMESTIC) SOURCE
REQUIREMENTS AND EVALUATION
CRITERIA
REQUIREMENTS & EVALUATION CRITERIA

* $\Delta R/R$ or RADIUS OF CURVATURE PRECISION
  * ABSOLUTE SURFACE ACCURACY A KEY ISSUE FOR COHERENT SEGMENTED PERFORMANCE
  * CONCLUDED THAT 1.5 TO 2-M PANELS MORE CAPABLE OF MEETING THIS REQ'T THAN 4-M ONES

* $\Delta R/R$ DRIVES:
  * PANEL SIZE
  * MAT'L SELECTION re. CTE HOMOGENEITY
  * PRODUCIBILITY
    BLANK MANUFACTURE
    OPTICAL PROCESSING
  * AND SHAPE, QUANTITY REQ'D,......
FIG. 3  WAVEFRONT ERROR BUDGET

DIFFRACTION LIMITED PERFORMANCE AT 30\mu m = \frac{30}{18.7} = 2.2 \mu m rms

---

**STATIC SYSTEM WAVEFRONT**
\( \Delta Wf = 2.2 \mu m \) rms

---

**SECONDARY MIRROR**
\( \Delta Wf = 1.5 \mu m \) rms

---

**PRIMARY MIRROR**
\( \Delta Wf = 2.1 \mu m \) rms

---

**PRIMARY/SECONDARY ALIGNMENT**
\( \Delta Wf = 0.5 \mu m \) rms

---

**ALIGNMENT TESTING & CONTROL**
\( \Delta Wf = 1.2 \mu m \) rms

---

**REFLECTOR PANELS**
\( \Delta Wf = 1.7 \mu m \) rms

---

**FABRICATION**
1.2 \mu m rms

---

**MANUFACTURING**
1.2 \mu m rms

---

**METROLOGY**
\( \Delta R = 0.5 \) \mu m

---

**DESIGN RESIDUALS**
6.6 \mu m rms

---

**EXTERNAL EDGE EFFECT**
\( \Delta S = 0.5 \) \mu m

---

**GAP EFFECTS**
\( \Delta S = 0.5 \) \mu m

---

**MASS REMOVALS**
\( \Delta S = 0.5 \) \mu m

---

**MECHANICAL**
6.0 \mu m

---

**THERMAL**
1.2 \mu m

---

**OPERATION**
1.2 \mu m rms

---

**DESIGN, RELEASE**
\( \Delta R = 0.5 \) \mu m

---

**RESIDUAL LOAD**
\( \Delta S = 0.5 \) \mu m

---

**MOUNT CLEARANCES**
\( \Delta S = 0.5 \) \mu m

---

**TEMPERATURE EFFECTS**
\( \Delta S = 0.5 \) \mu m

---

**AXIAL C.G.D.**
\( \Delta S = 0.5 \) \mu m

---

**LATENZO C.G.D.**
\( \Delta S = 0.5 \) \mu m

---

**NOTES:**

1. \( \Delta S = \) WAVEFRONT ERROR DUE TO FIGURE CHANGE (\mu m)

2. \( \Delta R = \) " " " " RADIUS CHANGE (\mu m)

3. \( \Delta R \) WAVEFRONT ERROR = 0.95 \mu m \( \mu m \)

---

From: Doc
THE ΔR/R INFLUENCE TREE

ΔR/R
CTE AXIAL HOMOGENEITY DIFFICULTY INDEX

1-m | 1.5-m | 2-m | ... | 4-m
1 | 80 | 7.4 | ... | 2.4

TRADEABLE WITH:
ACTUATORS/m²
EDGE EFFECTS
SENSING & CONTROL IMPLEMENTATION
DEPLOYMENT

1.5 - 2 m PANELS

UP TO 800 REQ'D FOR
A 30-m LDR

OPTICS MANUFACTURING
- ΔR/R INITIAL PRECISION
- OFF-AXIS ASPHERICS
- TIME

REPLICATE
ACCURATE PREFORMS

WEIGHT REQ'TS
- .15 kg/m² TERRITORY
- EQUIV. TO 1/4" SOLID GLASS
- FRAGILE MIRRORS
- AVOID MACHINING LOADS

SHAPE
HEX VS TRAPEZOID

TRAPEZIODES HAVE A TOOLING
ADVANTAGE

BUT, POWER MATT's

SOLID VS. SANDWICH VS. MAT'L & PROCESSES

REPLICABLE INVENTION REQ'D
~ AND WE DID!!~

HIP COBRAK CORNING PYREX QUARTZ ZODR
BERY. ALUM TGC
CURVATURE PRECISION

- Unique to coherent segmented mirrors.

- An initial manufacturing and....

- Material selection issue.
RADIUS OF CURVATURE PRECISION

BIG DRIVER FOR PHASED (COHERENT) OPERATION

\[ \Delta W F \approx \frac{1}{3} \left( \frac{r}{R} \right)^2 \Delta R \]

\[ \varepsilon \Delta R = \frac{R^2 \omega \Delta T}{h} \]

\[ \Delta W F = \frac{1}{3} r^2 \omega \frac{\Delta T}{h} \]

FAVORS SMALL PANELS
Fig. 4

**Req'd Radius of Curvature Precision**

\[
\frac{\Delta R}{R} = \left( \frac{3}{r^2} \right) \Delta WF_{rms}
\]

Example shown for f/1 double \( \frac{\Delta R}{R} \) values for f/2, etc.

**Fig. 4**
ABSOLUTE SURFACE PRECISION REQ'TS FOR PANELS

FIGURE PRECISION

\[
8 \times 10^{-6}
\]

EQUIV. TO \(\lambda/20\) rms WF

@ \(\lambda = 2 \mu m\)

OR

\[
\frac{A}{13} \text{ FIGURE @ } \lambda = \text{ 'VISIBLE'}
\]

\[
\pm 34 \times 10^{-6} \text{ in.}
\]

BASIC SHAPE

\[
0.28 \text{ in.}
\]

CURVATURE PRECISION

\[
\text{for } \lambda = 30 \mu m
\]

\[
* \text{ 20m f/1 o'ALL REFLECTOR}
\]
\[ \frac{Q}{R} = \frac{d^2}{8R} \cdot \frac{\Delta R}{R} \]

\[ \gamma = 0.028 \lambda \]

\[ \lambda = 30\, \text{mm} \]

\[ Q = 0.84\, \text{mm} \]

\[ R = 40 \]

\[ d = 1.5 \]

\[ \frac{\Delta R}{R} = 0.84 \times 10^{-6} \times 3 \times 40 / 1.5^2 \]

\[ \Delta R = 119 \times 10^{-6} \]

**EXAMPLE**

The text on the diagram is not legible due to the quality of the image. The equation shows a relationship between \(Q\), \(R\), \(d\), and \(\Delta R\), and there are some values given for \(\lambda\), \(Q\), \(R\), and \(d\) that lead to the calculation of \(\Delta R\). The diagram illustrates the concept of macro-quilting or \(\Delta R/R\).
\[
\begin{align*}
\Delta \delta & = \frac{r^2}{2R} \\
\Delta \delta \equiv \Delta \varphi & = -\frac{r^2}{2R} \left( \frac{\Delta R}{R} \right) \\
\Delta W & = \frac{1}{3.4} \frac{r^2}{R} \left( \frac{\Delta R}{R} \right) \\
\frac{\Delta R}{R} & = \frac{3.4 \Delta W R}{r^2} \\
\therefore \Delta \varphi & = -\frac{r^2}{2R} \times \frac{3.4 \Delta W R}{r^2} \\
\therefore \Delta \varphi & \equiv 1.7 \Delta W \\
\text{or} \\
\Delta W & = \frac{\Delta \varphi}{1.7}
\end{align*}
\]

WAVEFRONT ERROR \( \delta \) 
QUILTING AMPLITUDE
CTE AXIAL HOMOGENEITY (10°)

\[ \Delta x < \frac{3R \Delta W}{r^2 \delta} \]

(\text{NO PROBLEM})

AXIAL HOMOGENEITY

\[ \Delta x < \frac{3 \Delta W}{h} \]

TYPICAL

CLASS HOMOGENEITY REQUIREMENTS
NO. DIFFERENT HEXES TO FILL REFLECTOR DIA.

I.E. TOOLING REQS.
ASSESS EXISTING TECHNOLOGY
ASSESS EXISTING TECHNOLOGY

- ADEQUATE MATERIALS EXIST
  - HOMOGENEOUS
  - ISOTROPIC
  - IN PRODUCTION

- FULLY PROVEN PRODUCIBILITY METHODS DON'T
  - REPLICAIBILITY
  - ACCURACY
  - OPTICAL PROCESSING re. ......
  - FLEXIBILITY
  - MAT' L REMOVAL RATES
  - QUILTING
  - SUB SURFACE DAMAGE
  - PRODUCTION RATES ~ LIKE 2 PER WEEK!
  - COST/FACILITIES FOR BLANKS
  - DITTO FOR OPTICS OPERATIONS
PERFORMANCE / PRODUCIBILITY RELATIONSHIPS

- CTE homogeneity
- Inherent lightness
- Confidence

FUSED QUARTZ SANDWICHES, FOR EXAMPLE

PRODUCIBILITY
- Replicability
- Minimal cost
- Rapid delivery rates

GRAPHITE-EPoxy DISHES, FOR EXAMPLE
<table>
<thead>
<tr>
<th>CANDIDATE MAT'LS</th>
<th>COILF'GN APPPLICABILITY</th>
<th>FORMING TEMP</th>
<th>FRITS/ADHESIVES</th>
<th>DELIVERY RATE</th>
<th>CURRENT SIZE LIMIT</th>
<th>COST</th>
<th>ZN PERF</th>
</tr>
</thead>
<tbody>
<tr>
<td>HERAEUS FUSED QUARTZ</td>
<td>✓ ✓</td>
<td>2000°C</td>
<td>NO SL. 44'' H</td>
<td>YES</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SCHOTT ZERODUR</td>
<td>✓ ✓</td>
<td>800°C*</td>
<td>YES F. 290'' H</td>
<td>YES</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HIP BERYLLIUM</td>
<td>? 900°C</td>
<td>NO (F.) 48'' H</td>
<td>YES</td>
<td>M/H</td>
<td>YES</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&quot;COILZAK&quot;/AL. FOAM</td>
<td>✓ N/A</td>
<td>RT</td>
<td>YES F 80'' VL</td>
<td>NO</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*CANDIDATE MAT'LS & PRODUCIBILITY FACTORS

*SUBS. CERAMMING REQ'D
HERAEUS FUSED QUARTZ

- Most homogeneous mat'1 available
- No perceptible anisotropy
- $\alpha/K$ is OK
- Thin quartz shells have been formed
- 3-4% areal density cores have been made
- Very high company interest
SCHOTT ZGRODUR

- Adequate homogeneity, isotropy inferred from large casting data

- Formable in 'glass' state @ low temp precision forming work had been sponsored by DARPA, currently not being funded

- Thin section ΔC investigations req'd for solids

- Low temp frit devol. req'd for sandwiches

- Probably a good choice but requires up-front costs for material & process developments forming, joining, CTE "tuning"
GOOD POTENTIAL FOR "EL CHEAPO" MIRRORS

NOT MUCH DETAIL DATA AVAILABLE ON SPECIFIC MAT'L CHARACTERISTICS

PYREX PREFORMS & FRT DEVELOPMENT, CORE DESIGN

IT WILL TAKE A CONTRACT TO GET THIS WORK DONE AT CORNING, NO "FREEBEES"
OR WE COULD SET UP TO DO IT!!

INFERIOR TO QUARTZ & BERYLLIUM FOR DOD-TYPE APPLICATIONS

FUNDING WOULD NOT HAVE MULTI-AGENCY "PAYOFF"
HIP BERYLLIUM AT PEARSON-ELMER

Exciting new developments at PE

Small scale pieces show figure req'ts be met at 2000K, AR data lacking

Will mat'l be sufficiently homogeneous & isotropic at 3 to 5 times scale-up?

Considerable Gov't interest

This one is definitely worth watching!!
ALCOA "COILZAK" & ERG ALUMINUM FOAM

- THE CLOSEST APPROACH TO "... STAMPING OUT BIG MIRRORS"
- AS-RECEIVED SURFACE SMOOTHNESS GOOD
- GOLD COATING ENHANCES IR REFLECTIVITY
- WORRIES INCLUDE:
  - AL. SHEET IN-PLANE ORTHOTROPY
  - BOND-LINE MISMATCHES DUE TO WICKING
  - FORMABILITY TO:
    - $8 \times 10^{-6}$ WAVINESS FOR 2 M PERF.
    - $100 \times 10^{-6}$ " " 30 M PERF.
**Fig. 9** "STAMPED" METAL MIRRORS

**COILBAK PREFINISHED SHEET**
- .03" thick
- 1000 A" rms

AS RECEIVED

GOLD OVERCOAT

**EPS FRAMED ALUMINUM CORE**

**THERMAL MOMENT**

\[ M_T = f(\Delta T, \Delta T) \]

WICKING & LACK OF UNCERTAINTY IS PROBLEM TO BE RESOLVED

**FOCUSED DIE OF CORRECT RADIUS & OPTICAL PRESCRIPTION**

**FOCUSED MIRROR FACEDNESS**

.03" ALUMINUM COILBAK FACESHIELD

FINISHED ALUMINUM MIRROR READY FOR OPTICAL COATINGS

ASSEMBLING THE SANDWICH ON THE FOCUSING DIE
**COILZAK/ALUMINUM MIRRORS: THE Δt_2 BONDLINE ISSUE**

**COILZAK**

**ΔT=170°F**

**ERG ALUM FOAM**

**ADHESIVE**

\[
M = \frac{(\alpha_2 - \alpha_1) t_1 \Delta T}{2 \left( \frac{1}{t_1 E_1} + \frac{1}{t_2 E_2} \right)}
\]

\[
\Delta \delta = -\frac{r^2}{2R} \left( \frac{\Delta R}{R} \right)
\]

\[
\Delta \delta = \frac{Mr^2}{2EI} \quad \xi = \frac{tH^2}{2}
\]

\[
\Delta t_2 \leq \frac{(E_1 t_1 H^3) \Delta R}{22R}
\]

\[
t_2 - t_2 = \Delta t_2
\]
ALLOWABLE $\Delta t_2$ VALUES, AN EXAMPLE

$$\Delta t_2 = \left( \frac{E_1 t_1 H^2}{22R} \right) \frac{AR}{R}$$

for $R = 1600$ in $\& \frac{AR}{R} = 125 \times 10^{-6}$

i.e. 60" PANELS FOR A 20-m f/1 REFLECTOR

<table>
<thead>
<tr>
<th>$t_1$</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>.01 in.</td>
<td>.0036 in.</td>
<td>.0014</td>
<td>.0032</td>
<td>.0056</td>
</tr>
<tr>
<td>.015</td>
<td>.0054</td>
<td>.004</td>
<td>.0048</td>
<td>.0084</td>
</tr>
<tr>
<td>.02</td>
<td>.0072</td>
<td>.0028</td>
<td>.0064</td>
<td>.011</td>
</tr>
<tr>
<td>.025</td>
<td>.009</td>
<td>.0035</td>
<td>.008</td>
<td>.014</td>
</tr>
<tr>
<td>.03</td>
<td>.011</td>
<td>.0042</td>
<td>.0096</td>
<td>.017</td>
</tr>
</tbody>
</table>

$K_g/m^2$ | 6 → 8 | 11 → 13 | 16 → 18 | 21 → 23

$\Delta t_2$ PROBABLY OK BUT NO $K_g/m^2$ PAYOFF!
COILZAK MIRRORS/CONCLUSIONS

- Δt₂ control @ λ=30 μm coherent performance risky!
- Could represent a gigantic cost & schedule saving
- But doubtful applicability to other programs, not much chance of support—!
- No further consideration
HYBRID MIRROR CONCEPT

PERMITS RADIUS OF CURVATURE ADJUSTMENT AS REQ'D TO
ACHIEVE CONVENT STABLE WAVEFRONT PERFORMANCE

MUTLITY SUPPORTED PRE-FORMED
"OILZAK" MIRROR SURFACE

ATTACHMENT "BUTTON"

AXIAL SUPPORT ROD

ALUMINUM SHEET
"FOAM" SHEET
SANDWICH
BONDED OR BRAZED

CONCEPT ALSO APPLICABLE TO:
CLASS
GE-NG
COMBINATION!
Composites were also evaluated.

- They did not pass the ΔR/Δr criterion for coherent operation.
- Problem lies with part-to-part CTE variability.

\[ \Delta T \approx 170^\circ F \]

<table>
<thead>
<tr>
<th>2r</th>
<th>4&quot;</th>
<th>8&quot;</th>
<th>12&quot;</th>
<th>16&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>40&quot;</td>
<td>0.004</td>
<td>0.008</td>
<td>0.012</td>
<td>0.016</td>
</tr>
<tr>
<td>60&quot;</td>
<td>0.018</td>
<td>0.035</td>
<td>0.053</td>
<td>0.07</td>
</tr>
<tr>
<td>80&quot;</td>
<td>0.001</td>
<td>0.002</td>
<td>0.003</td>
<td>0.004</td>
</tr>
</tbody>
</table>

\[ \frac{\Delta \alpha}{\Delta T} \] (ppm/°F)

Typical "best-effort" results:
- ST Metering Truss —— 0.03
- ST Fine Guidance Sensor —— 0.04
- ST Focal Plane Str —— 0.12

Achievable Δα precision (ppm/°F)
ANALYTIC STUDIES AND
PERFORMANCE PREDICTIONS
ANALYTIC STUDIES & PERFORMANCE PRED'NS

• THERMAL ENCLOSURE CRITICAL TO PERFORMANCE

"CHALLENGES"......
STRUCTURAL CONCEPTS
STOWAGE & DEPLOYMENT
DYNAMICS & POINTING

• SOLID MIRRORS BENEFIT FROM INITIAL CURVATURE

ABOUT A 45% STIFFNESS INCREASE
TRADE SOL'NS (HAND ANALYSES) CONSERVATIVE & SAFE
CORNERS OF TRAPEZIODS DON'T CURL
LDR THERMAL GOAL

- Almost any material will be OK if
  
  A) It doesn't "warp" between room temperature and 150°K
  
  B) The mirror is in a benign environment, i.e., constant uniform
  
- And of course cold

- The thermal enclosure design objective is to do all of this and do it passively
THERMAL ANALYSIS

OBJECTIVE

INVESTIGATE THERMAL STABILITY OF LDR MIRROR SEGMENTS
- MINIMIZE ENVIRONMENT CHANGES
- MAINTAIN MIRROR SURFACE AT LOW TEMPERATURES PASSIVELY

METHOD

DETERMINE PASSIVE ENCLOSURE DESIGN
ANALYZE MIRROR SEGMENTS

STATUS

- ENCLOSURE DESIGN CONCEPT COMPLETE
- SEGMENT THERMAL MODEL OPERATIONAL
- SEGMENT THERMAL ANALYSIS UNDERWAY

R.G.B. 2/23/82
### LDR Enclosure Design Concept

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forward Enclosure Length (L)</td>
<td>Controls energy irradiating/absorbed by the LDR</td>
</tr>
<tr>
<td>Enclosure MLI</td>
<td>Minimizes side to side gradients with MLI maximum gradient change &lt; 1° F</td>
</tr>
<tr>
<td>Radiator/Shade</td>
<td>Provides an area for earth IR and albedo energy rejection</td>
</tr>
<tr>
<td>Sun Shade</td>
<td>Eliminates the possibility of the sun irradiating the interior of the forward enclosure</td>
</tr>
<tr>
<td>Material Absorptivity (α)</td>
<td>THERMAL RADIATION PARAMETERS</td>
</tr>
<tr>
<td>Emissivity (e)</td>
<td>- External Enclosure α/e = 0.1/0.8</td>
</tr>
<tr>
<td></td>
<td>- LDR α/e = 0.1/1.1</td>
</tr>
<tr>
<td></td>
<td>- Internal Enclosure α/e = 0.8/0.8</td>
</tr>
</tbody>
</table>
Maximum Energy Absorbed By The Reflector

Energy ~ BTU/HR FT²

L/D

Equatorial Orbit

Flux Load

Solar 457 BTU/HR FT²
Earth IR 87 BTU/HR FT²
Earth Albedo 192 BTU/HR FT²

L D
# LDR Enclosure Temperature

## Forward Enclosure Temperature

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Temperature °F</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Radiator</td>
<td>Maximum: 83</td>
</tr>
<tr>
<td>Albedo Radiator</td>
<td>-105</td>
</tr>
<tr>
<td>Moveable Shade</td>
<td>-105</td>
</tr>
</tbody>
</table>

## Aft Enclosure Temperature

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Temperature °F</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Radiator</td>
<td>Maximum: 83</td>
</tr>
<tr>
<td>Albedo Radiator</td>
<td>-105</td>
</tr>
<tr>
<td>Moveable Shade</td>
<td>-105</td>
</tr>
</tbody>
</table>

## Absorbed Energy

- Maximum: 1.5 Btu/HR FT²
- Side to Side Variation ≈ 10%

## Side to Side Gradient

Less than 1 °F
INFLUENCE OF ΔR/R ON AN OTHERWISE PERFECT IMAGE

99% \[ \neq \] L INTENSITY

.3% OF CENTRAL SPOT INTENSITY

9x SPOT SIZE

20 mQ 5/1
2 m PANELS, TRAPEZIIDS
\( \lambda = 30 \, \mu m \)
\( \lambda/30 \) P-P "QUILTING" ERROR, I.E. \( \Delta R/R \rightarrow 0.5 \, \mu m \, \text{rms} \, \text{WF} \)
DESIGN DEFINITION
AND CONCEPT SELECTION
DESIGN DEFINITION & CONCEPT SELECTION

- HERAEUS FUSED QUARTZ
  ULTRA LIGHT 15 kg/m² OPTIMIZED SANDWICH
  PLUS.....
  OPTICAL STYLUS
  QUILTING POST
  SEMI-REPLICATED BLANK
  \{ PROducibility \}

- ALTERNATE MATERIAL CHARACTERIZATION TEST
  HOMOGENEITY
  FORMABILITY
  JOINABILITY
  \Delta Q'}
SELECTION LOGIC

- Emphasis is on sandwich configurations
- Little enthusiasm for thin solids outside of the LDR community (and myself)
- And we're looking for community-wide funding
- Why quartz? Performance confidence!
- Why alternate mat'ls search? Cost red'n & parallel source to solve the "2/week" issue
BUT...........

BY PRODUCING SOME EXTRA FACEPLATES FOR THE SANDWICH MIRRORS, WE CAN, AT MINIMAL COST, DO SOME THIN SHELL DEVELOPMENT WORK
* $\frac{5/3}{3} = 5000$ simulating
a full scale .1" faceplate,
1.5" cell mirror

**SHELL IN TOOLING FIXTURE ~ CONCEPT ONLY~**

NOT TO SCALE
W = 1.0 Kg/m²
f = 92 cps
\theta_{0.05} = 515 psi
\Delta_{\gamma} = 0.8 \lambda @ \lambda = 30 \mu m

MAT’L: HEPARUS FUSED QUARTZ
CORNING ALUMINO-SILICATE

OPTIMAL L.D.R. MIRROR PANEL
Optical stylus accurate to \( \frac{\lambda}{50} \) rms at \( \lambda = 2.8 \) mm

Linear interferometer ... \( \pm 1.118 \times 10^{-6} \)

Beam bending ............ \( \pm 2 \times 10^{-6} \) (residual calibration error)

Roller runout ............. N/A (see figure)

\[ \sum = 2.29 \times 10^{-6} \text{ in} \, \text{RSS} \]
PERKIN-ELMER COMPUTER CONTROLLED POLISHER (CCP) OPERATION CYCLE
Semi-replicated sandwich mirrors

- Large asphericities cannot be generated on ULW sandwiches ~ too fragile

- Molded in, i.e. semi-replication

- Spherically generated cores won't "match" the aspheric faceplate

- Unless the faceplate is "spherized"

- This can be done while the faceplate is "rigidized" on the mold form

- Then mirror is assembled
How to Make a "Replicated" Sandwich Mirror

- Produce the molding forms

Desired optical surface (concave, convex, on-axis, off-axis aspheric, etc.)

- Mold the glass

\[ \frac{t_{\text{req'd}} + \Delta}{h} \]

- Machine surface to spherical (R) contour

- Assemble parts

- Generate the core & backplate to spherical contours

- Touch-up & shine the optical surface
HOW TO AVOID QUILTING SIMPLY

2. CYANOACRYLATE BOND FERRULE TO MIRROR. EASILY REMOVED WITH HEAT AFTER FIGURING

3. EPOXY BOND FERRULE TO TUBE.

4. HEAT TO LOOSEN CYANO. MOVE RODS AFTER FIGURING IS COMPLETE

TUBE X-SECTION AREA
EQUAL TO CROSS-RIB AREA FOR EQUAL COMPLIANCE

P = 0.15 lbs

1. INSTALL TUBE & FERRULE FOR CENTERING

- 16:1 FACEPLATE STIFFNESS INCREASE
- 2.5:2 EQUIVALENT THICKNESS INCREASE
- FOR DIMENSIONS SHOWN, POST INCREASE 5/8" FROM 5056 TO 3/16, OUT OF THE QUILTING CONCERN RANGE
EQUIVALENT
PHENOMENOLOGY
MODEL

K₁ Core
K₂ Reinforced Core
K₃ Polishing Pad
K₄ Facplates
K₅ Tool (Very stiff)
K₆ Support

OUTPUT: Force in springs K₃ as a function of K₁, K₂, K₄ and position of pad along direction R.

Figure 3

SIMPLIFIED SKETCH OF TOOL PRESSURE VARIATION/QUILTING MODEL
APPARATUS FOR THRU-THE-THICKNESS CTE M'ENTS
TECHNOLOGY
DEVELOPMENT PLAN
TECHNOLOGY DEVELOPMENT PLAN

- PRODUCE A 40" \underline{HERAEUS} MIRROR @ 15 kg/m² TO $\frac{\lambda}{40}$ @
  - INCLUDING THE:
    - OPTICAL STYLIST
    - QUILTING POST
    - GRAPHITE DIES
    - etc
  - AND CONDUCT SCALE-UP FACILITIES IMPACT STUDY

- LOW LEVEL FUNDING TO \underline{CORNING FOR DEVELOPMENT}
  - OF A DOMESTIC BLANK SOURCE
    - \underline{PYREX ULW}
    - \underline{TGC}
SCHEDULE

<table>
<thead>
<tr>
<th>FY 83</th>
<th>FY 84</th>
<th>FY 85</th>
<th>FY 86</th>
<th>FY 87</th>
</tr>
</thead>
<tbody>
<tr>
<td>TASK AREA</td>
<td>0</td>
<td>3</td>
<td>6</td>
<td>9</td>
</tr>
</tbody>
</table>

THIN SHELL FIGURING

- EXP'T (AND 10 3/2"
- SHELLS REL FROM MFRS OR 3/80)

- THRU THE THICKNESS
  HOMOGENEITY

OPTICAL STYLUS DEVELOPMENT

- IR INTERFEROLOGY DEVELOPMENT

- 12" X ULW S/HIGH
  PRODUCIBILITY
  QUANTIFING AVOIDANCE
  NT DEVELOPMENT

- 24" X
  AS ABOVE BUT AT 2X SCALE-UP

- 40" X
  FULL MECH & THERMAL QUALITY

SCALE-UP STUDIES

- FACILITIES & COST
  PROJECTIONS FOR 15-24"
  BLANKS AT 1 PER WEEK
  CORNIS
  VERMEERSCHOTT
  (SCHOTT)

LARGE SCALE BULK SHELL DEVELOPMENT PROGRAM

- FIGURING & HOMOGENEITY 0.5" & IF DESIRO

- VERIFY BULK SHELL FEASIBILITY

- LASER CASE DRIFT TRANSFER

- COULD COMMENCE IN FY '83 IF 30-60"K IS AVAILABLE

- MOUNT DEVELOP.

- FULLY QUALIFIED
  26 16 60"
  "COLD" MIRROR

KEY

- O ORDER BLANKS
- R RECEIVING
- F FIGURE
- T THERMAL TEST
- V VISUAL TEST
- M HT WIT’G

ULTRA LIGHTWEIGHT IR MIRROR DEVELOPMENT

PROGRAM FOR LDR
IDENTIFY AND EVALUATE
PRIME TECHNOLOGIES
IDENTIFY & EVALUATE PRIME TECHNOLOGIES

- FUSED QUARTZ
  VIRTUALLY GUARANTEED PERFORMANCE....
  IF WE CAN MAKE IT LIGHT ENOUGH
- AND IF IT'S LIGHT ENOUGH
  CAN WE MAKE IT?

- WEIGHT DRIVEN CONFIGURATIONS & PRODUCIBILITY
TOTAL AVAILABLE P/L WEIGHT
53000 lbs

<table>
<thead>
<tr>
<th>Component</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPACECRAFT</td>
<td>10,000</td>
</tr>
<tr>
<td>THERMAL ENCLOSURE</td>
<td>3000</td>
</tr>
<tr>
<td>SCIENCE INST'S</td>
<td>8000</td>
</tr>
<tr>
<td>ELEC &amp; SENSORS</td>
<td>2000</td>
</tr>
<tr>
<td>REFLECTOR</td>
<td>30,000</td>
</tr>
</tbody>
</table>

INTEGRATING STR.
ACTUATORS
PANELS

7500  7500  15000 lbs

WEIGHT BUDGET NOT MUCH AVAILABLE FOR 20+ m LDR'S
<table>
<thead>
<tr>
<th>DIAMETER</th>
<th>AREAL DENSITY</th>
<th>EQUIV. SOLID THICKNESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 m</td>
<td>87 Kg/m²</td>
<td>1.6 inches</td>
</tr>
<tr>
<td>15</td>
<td>39</td>
<td>.7</td>
</tr>
<tr>
<td>20</td>
<td>22</td>
<td>.4</td>
</tr>
<tr>
<td>25</td>
<td>14</td>
<td>.25</td>
</tr>
<tr>
<td>30</td>
<td>10</td>
<td>.18</td>
</tr>
</tbody>
</table>

**EQUIVALENT "SOLID" GLASS THICKNESS for 15,000 lbs**

15 Kg/m² is new technology for 1½ - 2 m mirrors
WHAT CAN BE DONE WITH 

1/4" EQUIVALENT SOLID THICKNESS?

- LEAVE IT "AS IS", i.e. THIN SHELL MIRRORS

- MAKE A ULTRA LITE WEIGHT SANDWICH
SOME TRADE ISSUES REGARDING . . . .

. . . . SOLIDS vs. "SAUCONCIBLES"

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Critical</th>
<th>Less Critical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thru-the-thickness CTE variability</td>
<td>$2 \times 10^{-6}$</td>
<td>$1.5 \times 10^{-5}$</td>
</tr>
<tr>
<td>First mode $&gt; 100$ ps</td>
<td>1 - 1.5 mΩ limit</td>
<td>2 mΩ OK</td>
</tr>
<tr>
<td>Stress, mounting</td>
<td>$0.75$ mΩ limit @ 10 g</td>
<td>2 mΩ OK</td>
</tr>
<tr>
<td>Self wt. defl'n</td>
<td>1800 μm</td>
<td>72 @ 2 Hz @ 2 mΩ</td>
</tr>
<tr>
<td>Producibility</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blank manufacture</td>
<td>SIMPLE, &quot;CHEAP&quot;</td>
<td>ADVANCED TECHNIQUES, $$$'s</td>
</tr>
<tr>
<td>Figuring</td>
<td></td>
<td>&quot;... several inventions req'd&quot;</td>
</tr>
<tr>
<td>Quilting</td>
<td></td>
<td>THE &quot;QUILTING POST&quot; INVENTION</td>
</tr>
</tbody>
</table>
MATERIAL SELECTION IMPLICATIONS

- **SOLIDS**
  \[ \Delta(\kappa) \leq 2 \times 10^{-10}/F \]
  - HERAEUS QUARTZ:* 1.3% HOMOGENEITY, ISOTROPY  OK
  - SCHOTT ZERODUR  0.7%  "  "  OK
  - CORNING "CANDIDATE")  ???

- **SANDWICHES**
  \[ \Delta(\tau) \leq 1.5 \times 10^{-3}/F \]
  - HERAEUS QUARTZ  1% \{ FACEPLATE MATCHING  OK
  - ZERODUR:* 2  6%  
  - 1-70 HIP BERYLLIUM  0.03% HOMOGENEITY (???) re \( \Delta P/R \)

*2 ALSO FRT DEVELOPMENT ISSUES

*OPTOSIL-III
**SOLID QUARTZ REFLECTOR PANELS**

(20m 5/1 BASELINE EXAMPLES SHOWN)

<table>
<thead>
<tr>
<th>PANEL SIZE</th>
<th>AREAL DENSITY (Kg/m²)</th>
<th>8</th>
<th>10</th>
<th>12</th>
<th>14</th>
<th>16</th>
<th>18</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-m</td>
<td></td>
<td>10</td>
<td>12.9</td>
<td>15.6</td>
<td>17.7</td>
<td>19.9</td>
<td>22.7</td>
<td>26</td>
</tr>
<tr>
<td>1.5m</td>
<td></td>
<td>4.4</td>
<td>5.3</td>
<td>7</td>
<td>2.9</td>
<td>8.9</td>
<td>10</td>
<td>11.4</td>
</tr>
<tr>
<td>2-m</td>
<td></td>
<td>2.5</td>
<td>3.2</td>
<td>3.9</td>
<td>4.4</td>
<td>5</td>
<td>5.7</td>
<td>6.4</td>
</tr>
<tr>
<td>THICKNESS</td>
<td>FIRST RESONANCE (CPS)</td>
<td>.14</td>
<td>.18</td>
<td>.22</td>
<td>.25</td>
<td>.28</td>
<td>.32</td>
<td>.36</td>
</tr>
</tbody>
</table>

- FAMILY OF THIN SOLIDS CAN MEET LDR FREQ REQ'SS
- VIABILITY OF DESIGN DEPENDENT ON:
  1) THRU-THE-THICKNESS CTE GRADIENT REPEATABILITY
  2) ELIMINATION OF SECONDARY OR REDUNDANT MOUNT CONSTRAINTS
  3) ABILITY TO FIGURE THIN SHELLS IN STRAIN-FREE CONDITION
A MORE CONSERVATIVE APPROACH

- a), b), & c) CRITICALITY DIMINISHED IF ....
- SANDWICH MIRRORS COULD BE BUILT AND POLISHED FOR THE SAME AREAL DENSITY.
- WE BELIEVE THEY CAN!
### Radial & Tangential Sagittal Differences (ΔSAC)

#### Panels in the outermost ring

<table>
<thead>
<tr>
<th>DIA (m)</th>
<th>5/No</th>
<th>R (m)</th>
<th>R₁ (m)</th>
<th>SAC₁ (m)</th>
<th>R₂ (m)</th>
<th>SAC₂ (m)</th>
<th>ΔSAC (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>5/1</td>
<td>40</td>
<td>41.11</td>
<td>.003041</td>
<td>43.43</td>
<td>.00288</td>
<td>.0064</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(41)</td>
<td>(.01219)</td>
<td>(43.071)</td>
<td>(.01161)</td>
<td>(.0231)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(21.93)</td>
<td>(.0229)</td>
<td>(26.37)</td>
<td>(.01896)</td>
<td>(.151)</td>
</tr>
<tr>
<td>40</td>
<td>5/5</td>
<td>40</td>
<td>44.50</td>
<td>.002809</td>
<td>55.08</td>
<td>.002269</td>
<td>.0213</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>(44.283)</td>
<td>(.01129)</td>
<td>(54.27)</td>
<td>(.00921)</td>
<td>(.0818)</td>
</tr>
</tbody>
</table>

*Non-bracketed values 1-m panels
Bracketted " 2-m "*
\[ W = \rho D^4 \frac{(1 - n + dn)^{1.5} E(1 - v^2)^{\frac{5}{2}}}{[E(1 - n^3) \Delta]^{5}} \]

\( \Delta \) = SPECIFIED DEFLECTION
\( n \) = CORE/OVERALL HEIGHT RATIO
\( \rho \) = " AREAL DENSITY
\( \rho_0 \) = MAT'LL DENSITY
\( D \) = MIRROR DIAMETER
The image contains a table and a diagram. The table includes columns for various parameters and values, and the diagram appears to be related to structural or engineering calculations. The handwritten notes suggest a discussion on mirror quality and the use of glass mirror examples. The text is handwritten in English, and the table is as follows:

<table>
<thead>
<tr>
<th>s</th>
<th>1/s</th>
<th>2/s</th>
<th>3/s</th>
<th>Overall Height G=6</th>
<th>Pa (kPa/m^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2000</td>
<td>1000</td>
<td>1000</td>
<td>2000</td>
<td>6000</td>
</tr>
<tr>
<td>1.5</td>
<td>.019</td>
<td>.107</td>
<td>.097</td>
<td>4.29</td>
<td>18.7</td>
</tr>
<tr>
<td>1.5</td>
<td>.023</td>
<td>.137</td>
<td>.098</td>
<td>5.4</td>
<td>21.8</td>
</tr>
<tr>
<td>1.5</td>
<td>.026</td>
<td>.117</td>
<td>.093</td>
<td>6.7</td>
<td>28.3</td>
</tr>
<tr>
<td>2</td>
<td>.02</td>
<td>.122</td>
<td>.117</td>
<td>3.3</td>
<td>22.1</td>
</tr>
<tr>
<td>2.5</td>
<td>.024</td>
<td>.134</td>
<td>.113</td>
<td>3.3</td>
<td>22.1</td>
</tr>
</tbody>
</table>

Figure 4

- Glass Mirror Example
- Δq = 24% - 26% for example
- g = 167 psi
- f = 329 cps

*Heraeus 37 cores & PE quilting avoidance will result in super lite-weight mirrors*
SCHEDULE
In the mid-1990s, NASA plans to orbit a giant telescope, whose aperture may be as great as 30 meters, for infrared and sub-millimeter astronomy. Its primary mirror will be deployed or assembled in orbit from a mosaic of possibly hundreds of mirror segments. Each segment must be shaped to precise curvature tolerances so that diffraction-limited performance will be achieved at 30 μm (nominal operating wavelength). All panels must lie within 1 μm on a theoretical surface described by the optical prescription of the telescope's primary mirror. To attain diffraction-limited performance, the issues of alignment and/or position sensing, position control to micron tolerances, and structural, thermal, and mechanical considerations for stowing, deploying, and erecting the reflector must be resolved. Radius of curvature precision influences panel size, shape, material, and type of construction. Two superior material choices emerged: fused quartz (sufficiently homogeneous with respect to thermal expansivity to permit a thin shell substrate to be drape molded between graphite dies to a precise enough off-axis asphere for optical finishing on the as-received a segment) and a Pyrex or Duran (less expensive than quartz and formable at lower temperatures). The optimal reflector panel size is between 1-1/2 and 2 meters. Making one, two-meter mirror every two weeks requires new approaches to manufacturing off-axis parabolic or aspheric segments (drape molding on precision dies and subsequent finishing on a nonrotationally symmetric dependent machine). Proof-of-concept developmental programs were identified to prove the feasibility of the materials and manufacturing ideas. Such a program would cost between $3M and $5M and could be completed in three to four years.