NASA CONTRACTOR REPORT 166493

LDR Segmented Mirror Technology Assessment Study

M. Krim
J. Russo

(NASA-CR-166493) LDR SEGMENTED MIRROR TECHNOLOGY ASSESSMENT STUDY Final Report (Perkin-Elmer Corp., Danbury, Conn.) 334 p HC A15/MF A01 CSCL 03A
N83-31549
Unclas
G3/89 13186

CONTRACT NAS2-11104
March 1983

NASA

NASA CONTRACTOR REPORT 166493

LDR Segmented Mirror Technology Assessment Study

M. Krim
J. Russo
Perkin Elmer Corporation
Electro-Optical Division/Optical Technology Division
100 Wooster Heights Road
Danbury, Connecticut

Prepared for
Ames Research Center
under Contract NAS2-11104

National Aeronautics and
Space Administration

Ames Research Center
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 um (nominal operating wavelength). All panels must lie within 1 um 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 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.

DISTRIBUTION:

NASA Headquarters
Washington, DC 20540
(1) Dr. Leonard Harris/RTM-6
(1) Dr. Lee Holcomb/RSI-5
(1) Dr. Martin Sokoloski/RTE-6
(1) Mr. Charles Bersch/RTM-6
(1) Dr. Michael Greenfield/RTM-6
(1) Mr. John DiBattista/RSS-5
(1) Dr. George Newton/SC-5
(1) Dr. John Warner/SC-7
(1) Dr. Nancy Boggess/SC-7

(2) Rome Air Development Center RADC/OCSE
Att: Captain Doris Hamill/J. Cusack
Griffiss Air Force Base, New York

(1) AF Weapons Laboratory AFWL/ARAA
Att: Dr. J. Fender
Kirtland AFB, NM 87117

(1) AFWAL/FIBAC
Att: Dr. George Holderby
Wright-Patterson AFB, OH 45433

(2) Aerospace Corp.
Att: Dr. Louis Reuben/Dr. Wayne Stuckey
MS A-6/1629
P.O. Box 92957
Los Angles, CA 90009

Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA 91109
(1) Dr. Paul Swanson/168-327
(1) Dr. Tom Kuiper/T-1165
(1) Dr. Steve Szirmay/198-326

Langley Research Center
Hampton, VA 23565
(1) Mr. William Boyer/158
(1) Dr. Martin Mikulas/190
(1) Mr. Ray Hook/364
(1) Mr. Wayne Slemp/224

(1) Lewis Research Center
Att: Mr. Charles Raquet
MS 54-5
Cleveland, OH 44135

California Institute of
Technology
1201 East California Blvd
Pasadena, CA 01125
(1) Dr. Tom Phillips
(1) Dr. Tom Leighton
(1) Dr. Tom Soifer

(1) University of California
Lawrence Berkeley Laboratory
Att: Dr. Jerry Nelson
Bldg. 50-351
Berkeley, CA 94720

(1) University of California
Department of Physics
Att: Dr. Paul Richards
Berkeley, CA 94720

(1) University of Arizona
Steward Observatory
Att: Dr. Roger Angel
Tucson, AR 84721

(1) Duke University
Department of Physics
Att: Dr. Frank Delucia
Durham, NC 27706

(1) University of Texas of Austin
Department of Astronomy
Att: Dr. Paul Vanden Bout
Austin, TX 78712

(98) NASA/Ames Research Center
Att: Mike Kiya/244-15
Moffet Field, CA 94043
(plus Camera-ready originals)

(1) Ames Reaseach Center
Patent Counsel
Moffet Field, CA 94043
N200-11A

(1) Ames Research Center
Technology Utilization Office
Moffet Field, CA 94043

Internal
(1) M. Krim/813
(1) J. Russo/879
(1) R. Babish/880
(1) R. Scott/089

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Continued)

LIST OF TABLES

SECTION 1

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 presciption 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
6. Selection of Two Most Promising Concepts and Preparation of Technology Development Plans.

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/m^2 are either too fragile from a mechanical and producibility aspect, or are too big too 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/m^2 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 considerabley 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 of 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 "gimmics", 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 2-1

TOP-LEVEL LDR REQUIREMENTS (FROM SOW AND ATTACHMENTS)

Overall Diameter	$10 \leq D \leq 30M$
Figure Type	Parabola or Hyperbola/Not Simply Spherical
Figure Quality	D/L @ 30 $\mu \rightarrow \lambda/13.7$ rms or $2.2\,\mu] \xrightarrow{\text{System}} 2\,\mu_{rms}$ Mirror
Speed	f/0.5 To f/1
Weight	25000 lbs (11360kg) Including Actuators
Operating Temp	150 - 200K (-100 to -190°F)
Operating W/L	2μ to 1000μ
Dynamics	0.00035g (Slew), F> 10 cps (Spatial Chopping)
Stability	Passive Segments Preferred
Technology Demon.	1987
Operational System	1993
Deployment	Single STS Flight, Manual Assist OK
Mission Duration	10 yrs

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 wave = 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 wave/20 and wave/40 rms at 2 micrometers, equivalent to wave/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, wave/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 wave/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

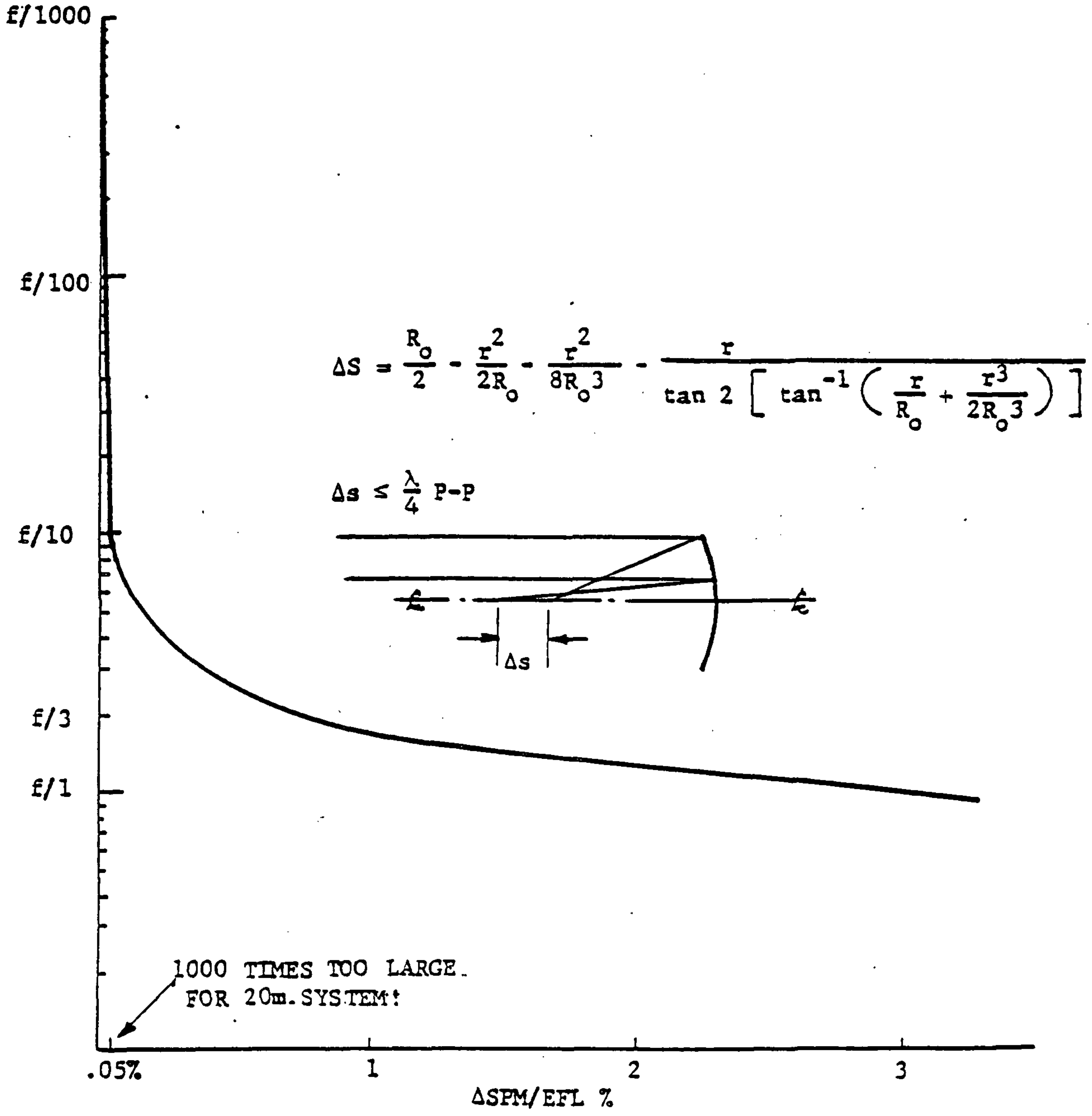


Figure 2-1. Longitudinal Spherical Aberration, Spherical Primary Mirror

TABLE 2-2

RADIAL AND TANGENTIAL SAGITTAL DIFFERENCES (ΔSAG) FOR PANELS IN THE OUTERMOST RINGS

DIA (m)	f/No	R (m)	R_1 (m)	SAG_1 (m)	R_2 (m)	SAG_2 (m)	ΔSAG (In)
20	f/1	40	41.11	0.003041	43.43	0.00288	0.0064
			(41)	(0.01219)	(43.076)	(0.01161)	(0.0231)
20	f/0.5	20	22.14	0.005646	27.14	0.00461	0.0409
			(21.93)	(0.0228)	(26.37)	(0.01896)	(0.151)
40	f/0.5	40	44.50	0.002809	55.08	0.002269	0.0213
			(44.283)	(0.01129)	(54.27)	(0.00921)	(0.0818)

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, $\overline{S}$, is denoted as ΔSAG. The table shows ΔSAG values for 1- and 2m panels. Only if the panels were as small as 0.125 in diameter would the error budget requirements on ΔSAG 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/m^2, very light by current standards. At 30m, this value is 9.5kg/m^2, 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 homogeniety of thermal expansion ($\Delta L/L$) both within a given segment and between segments. This will be reviewed in considerably more detail in Section 4.

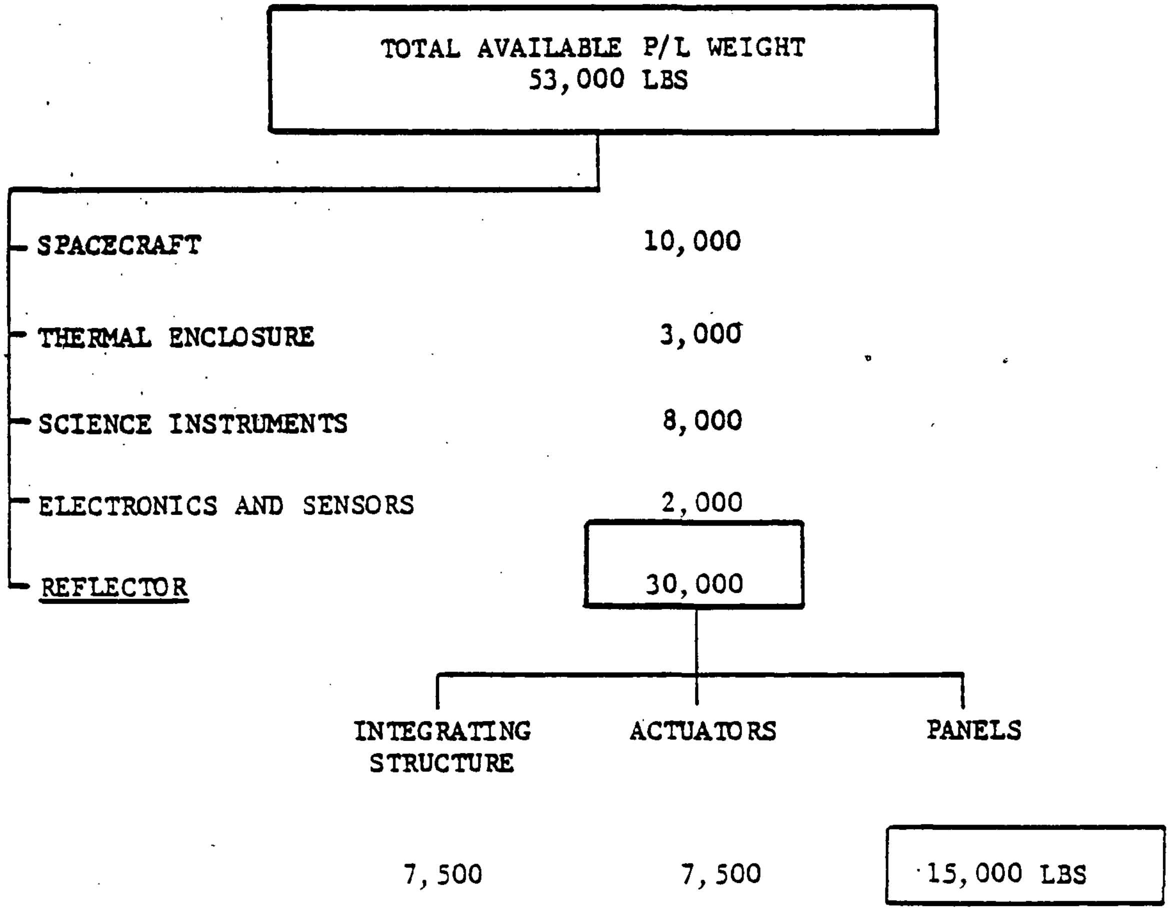


Figure 2-2. Weight Budget (Not Much Available for 20m+ LDRs)

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 expension (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.

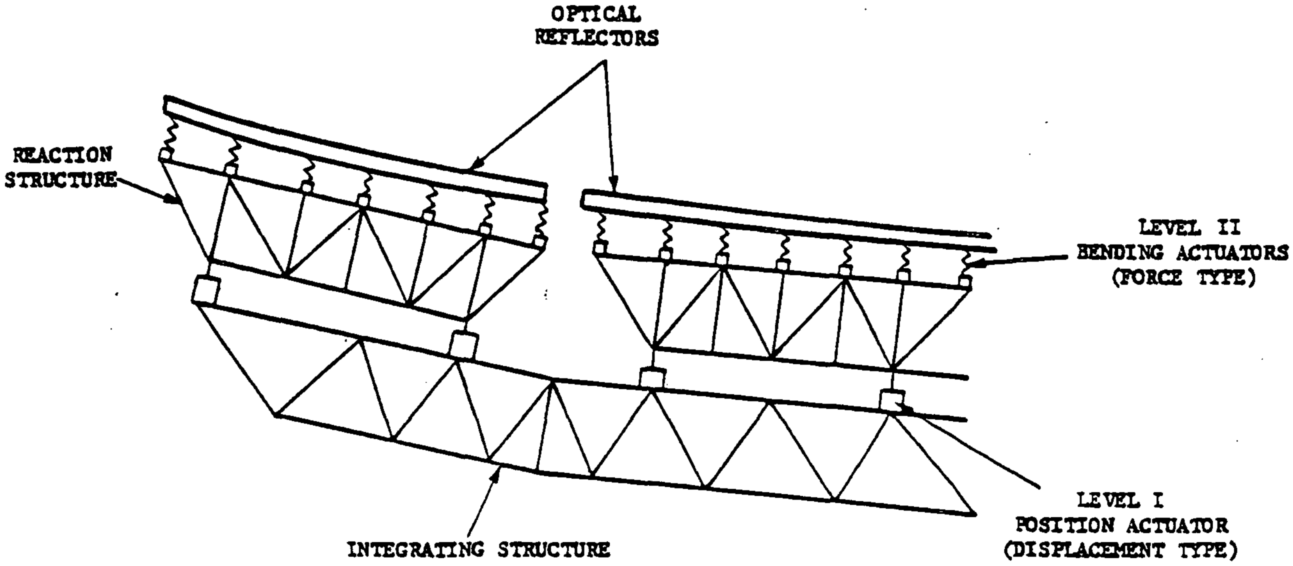


Figure 2-3. Figure Control Definitions (Schematic)

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

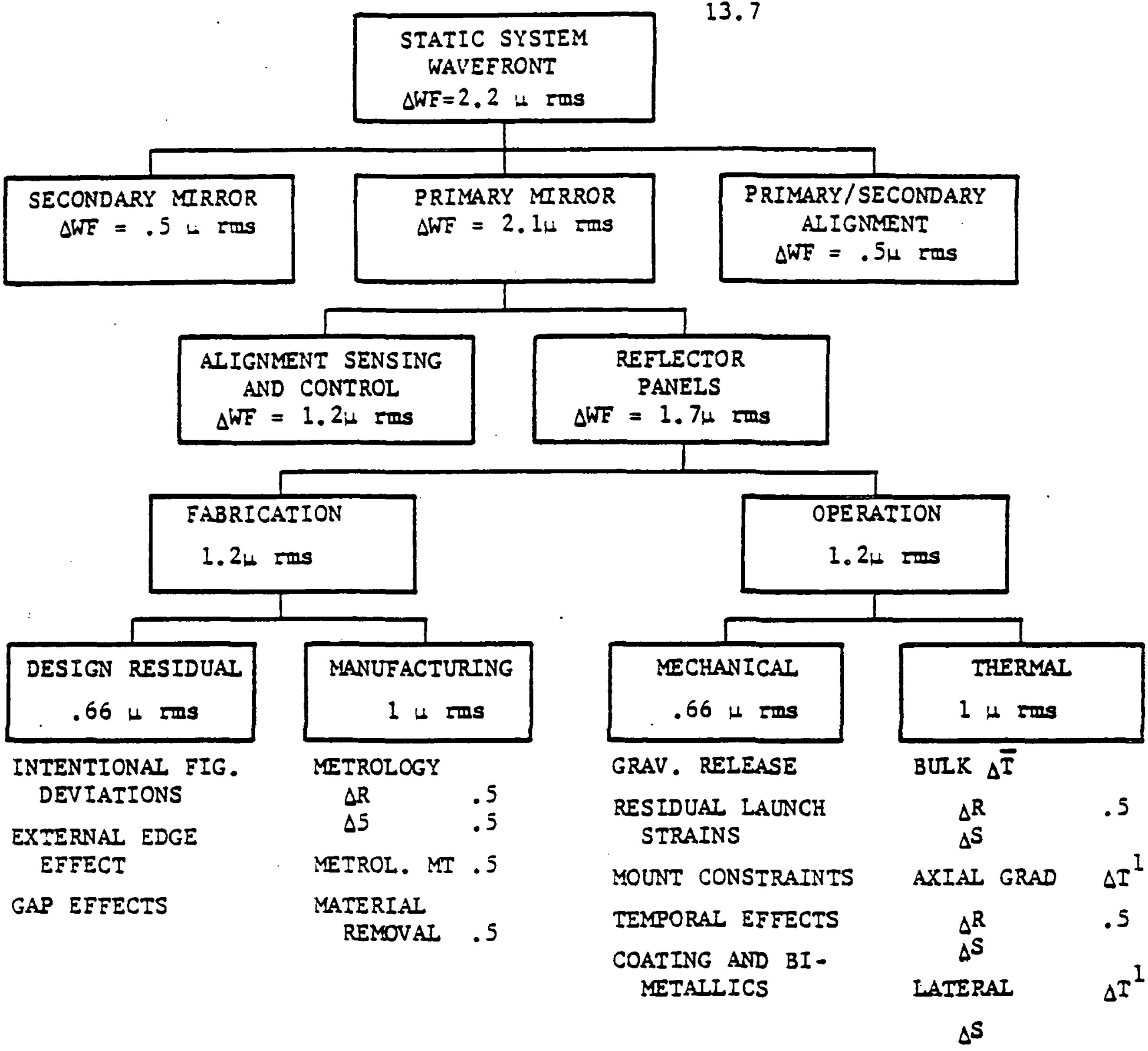
Figure 2-4 shows the error budget from which the panel performance and manufacturing requirements were derived. It presumes a two-mirror telescope whose static, jitter-free performance at the second focus is wave/13.7, a commonly accepted definition for diffraction-limited wavefront quality. Except for the ΔR 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

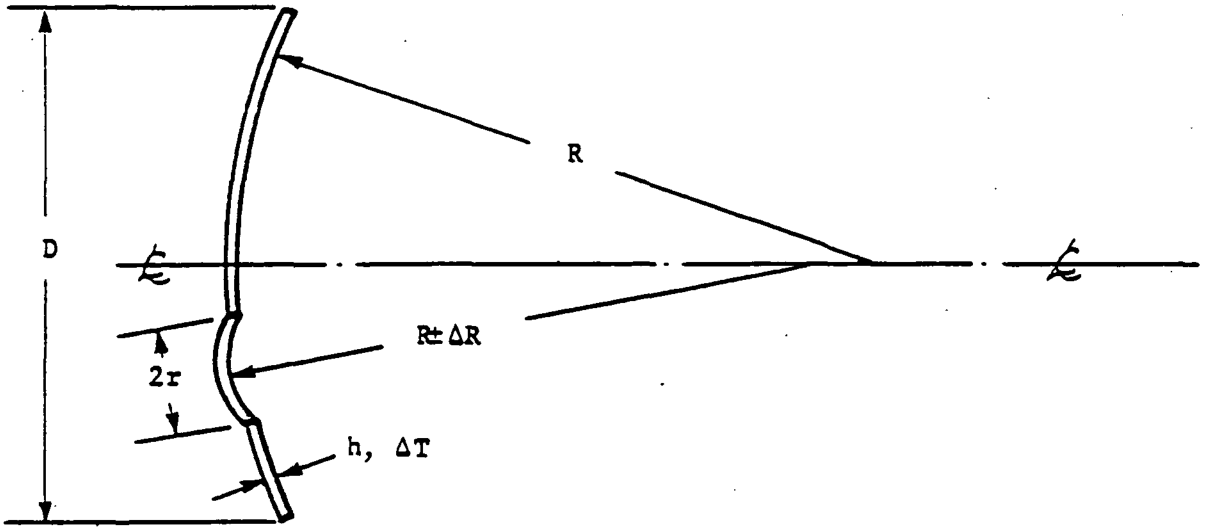


NOTES:

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



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

$$\Delta WF = 1/3\ r^2\, \alpha\, \frac{\Delta T}{h}$$

FAVORS SMALL PANELS

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

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

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

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

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

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

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

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 <u>absolute</u> surface contour error, from the familiar $\Delta = r^2/2R$ equation for the sagitta of a parabola, there is no size-dependent effect. Manipulation of the above equations shows that

$$I \Delta \simeq 1.7 \; WF_{rms}.$$

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 0.85 micrometer, or 30×10^{-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

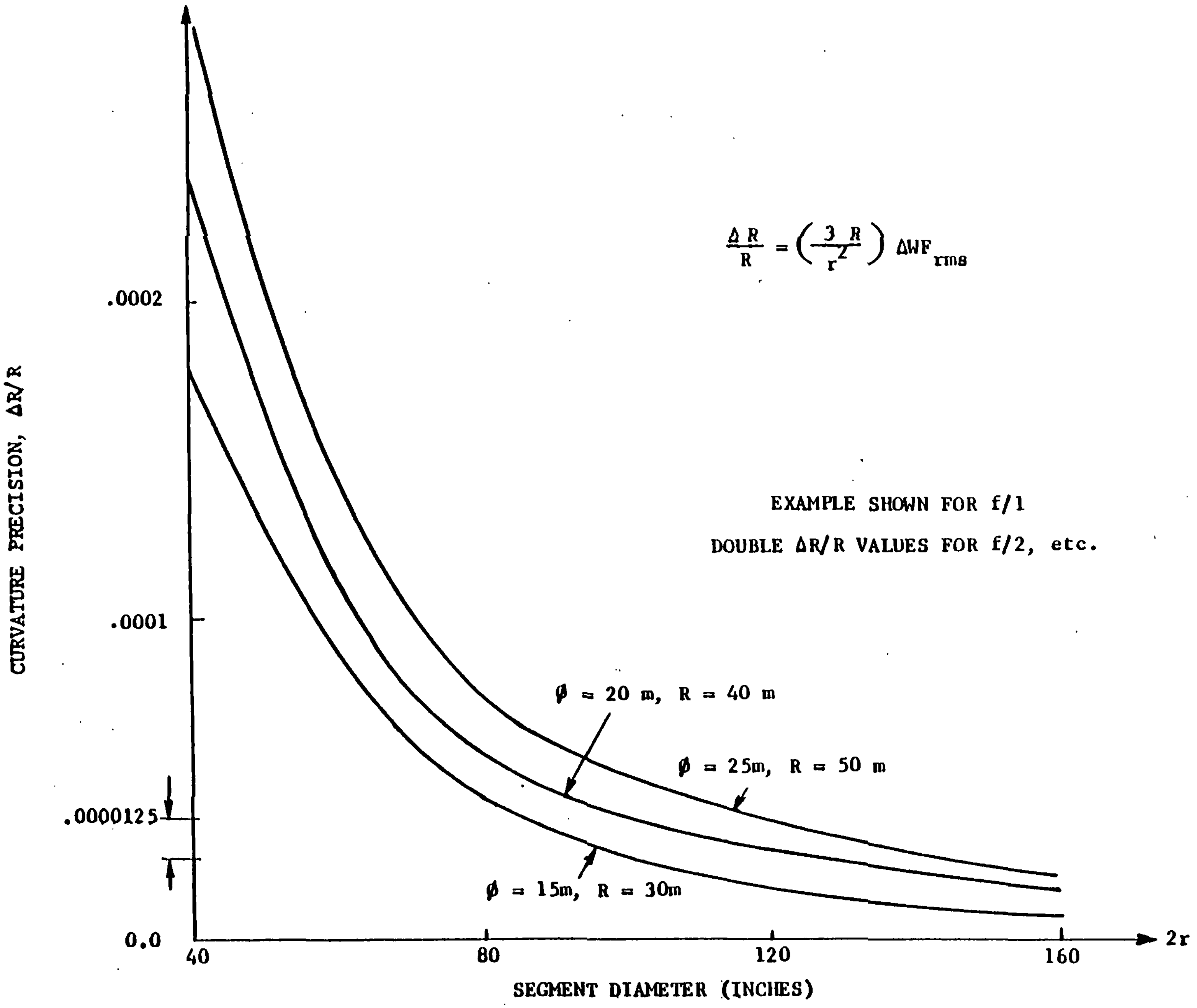


Figure 2-6. Required Radius of Curvature Precision for Wave/60 rms Coherence WF Error

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

$$\Delta\alpha' \leq \frac{3.46 \; \Delta WF_{rms} \; h}{r^2 \, \Delta \bar{T}} \; .$$

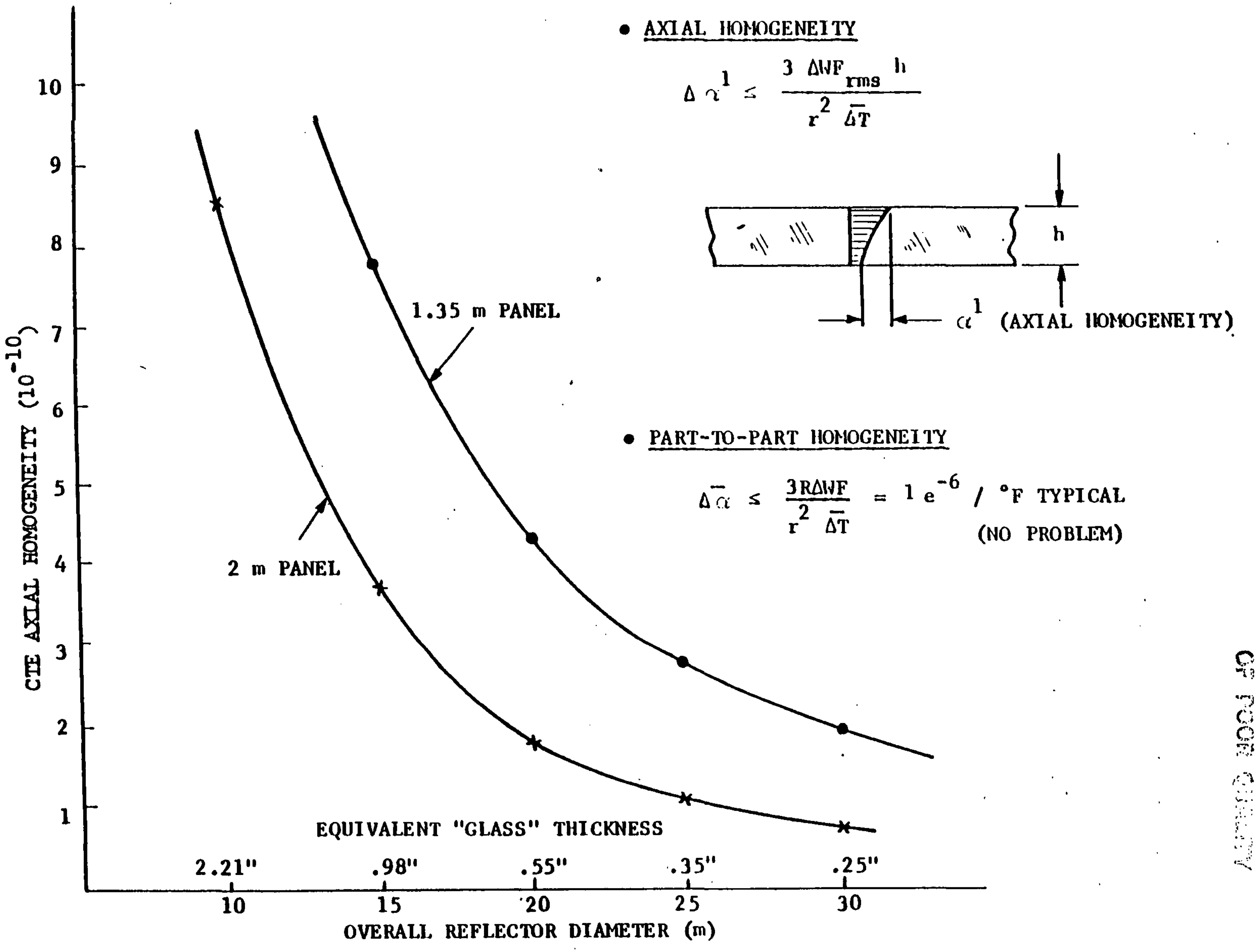
The terms in this equation are defined in Figure 2-7 where α' is axial inhomogeieity and $\Delta\bar{T}$ is the bulk average temperature change of the panel, approximately -170°F between factory and orbit. To relate overall reflector diameter to glass thickness "h", a constant reflector weight of 15,000 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 x 10^{-10} inhomogeneity value is approximately equal to one part in 750 for fused quartz and one part in 75 for Zerodur ($\bar{\alpha}$= 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 $\Delta\bar{T}$ 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 x 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.



- AXIAL HOMOGENEITY

$$\Delta \alpha^1 \leq \frac{3\ \Delta WF_{rms}\ h}{r^2\ \overline{\Delta T}}$$

- PART-TO-PART HOMOGENEITY

$$\Delta \overline{\alpha} \leq \frac{3R\Delta WF}{r^2\ \overline{\Delta T}} = 1\ e^{-6}\ /\ ^\circ F \text{ TYPICAL}$$

(NO PROBLEM)

Figure 2-7. Glass Homogeneity Requirements -- Thermal/Operational

ORIGINAL PAGE IS OF POOR QUALITY

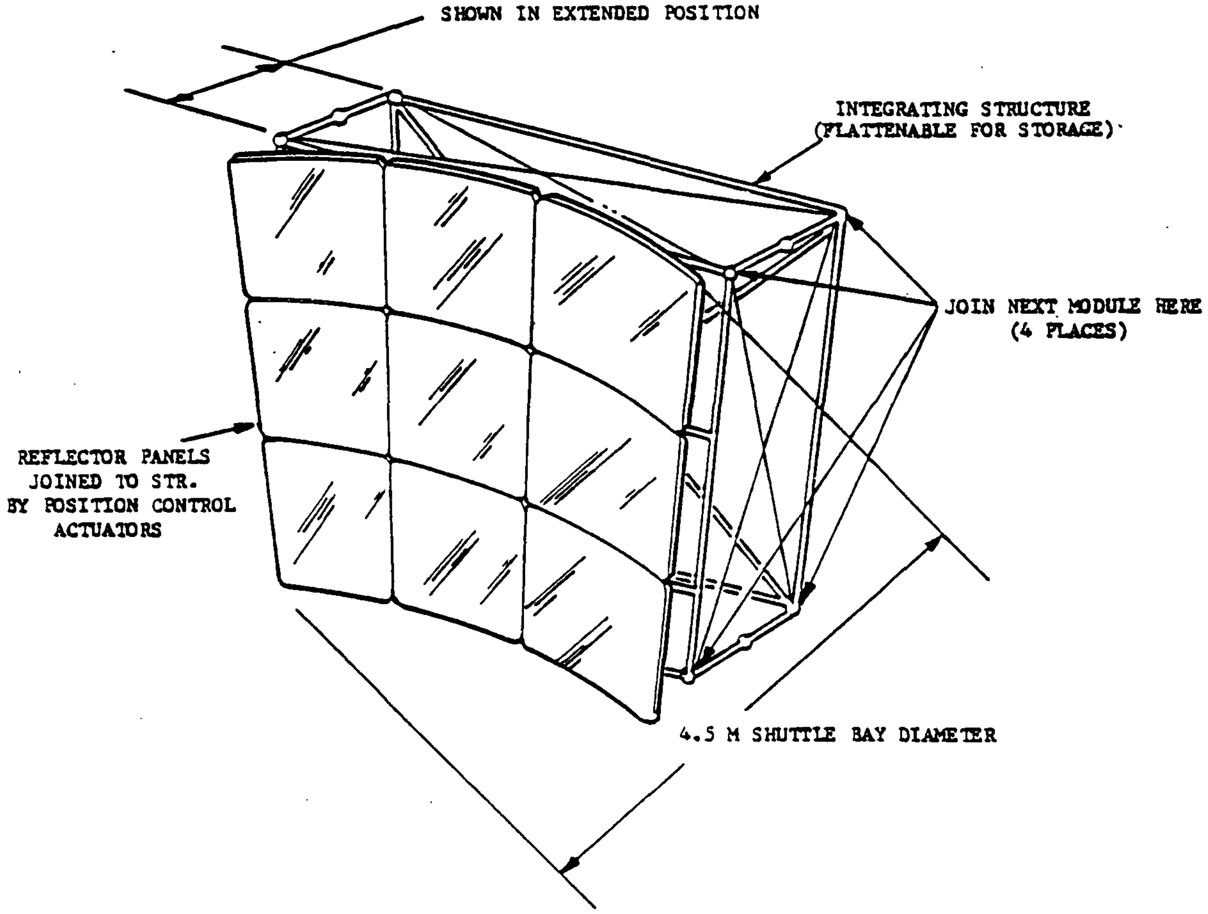


Figure 2-8. Preassembled Panel Module Concept

TABLE 2-3

PACKING EFFICIENCY

	Number		Area (m^2)	
Major Dimension	Hexagonal	Square	Hexagonal	Square
4m	1	1	12	10.1
2.5m	3		14	
2.25m		4		10.1
1.7m	7		15	
1.5m	7	9	11.8	10.1

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/m^2)
- 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/m^2 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.

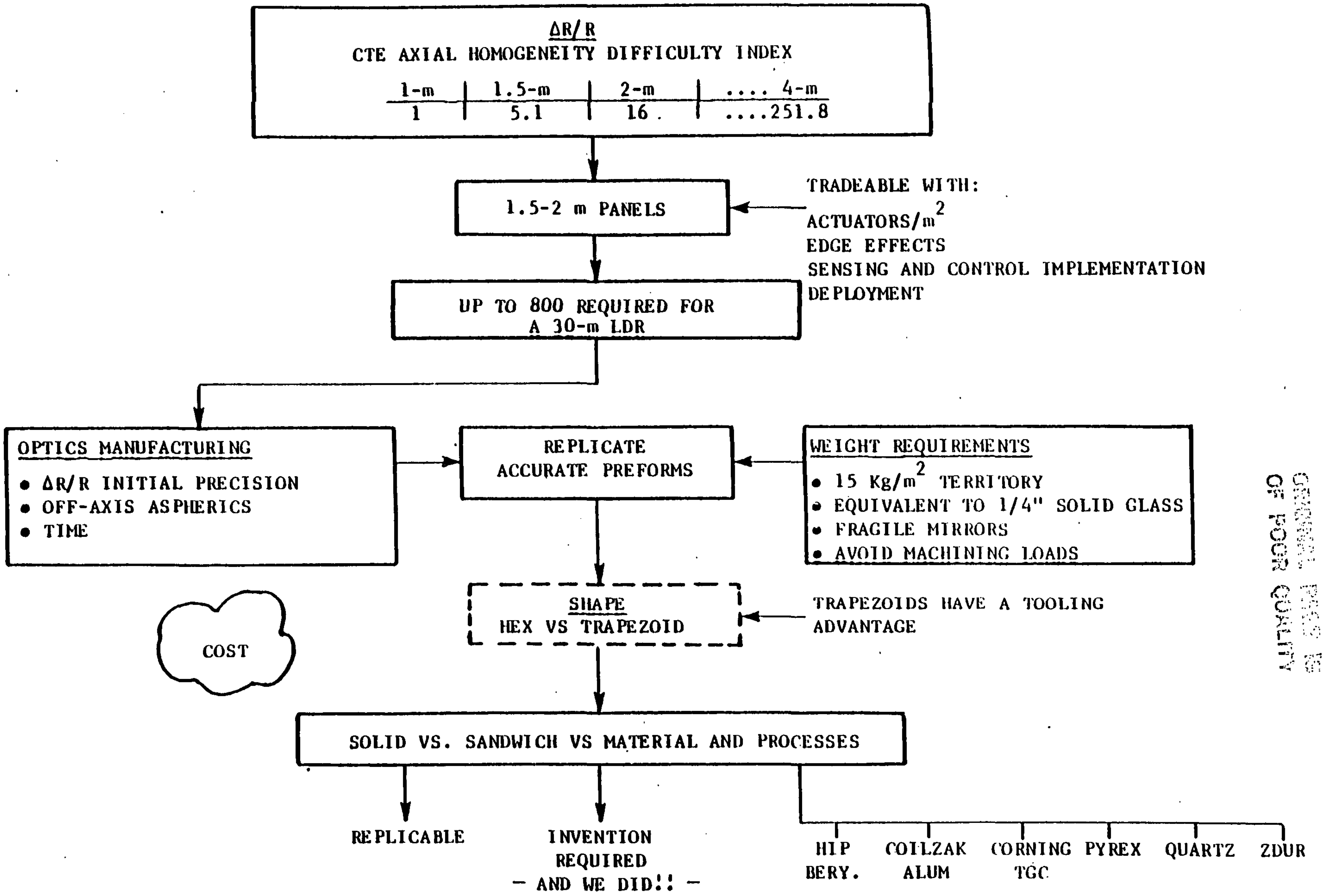


Figure 2-9. The ΔR/R Influence Tree

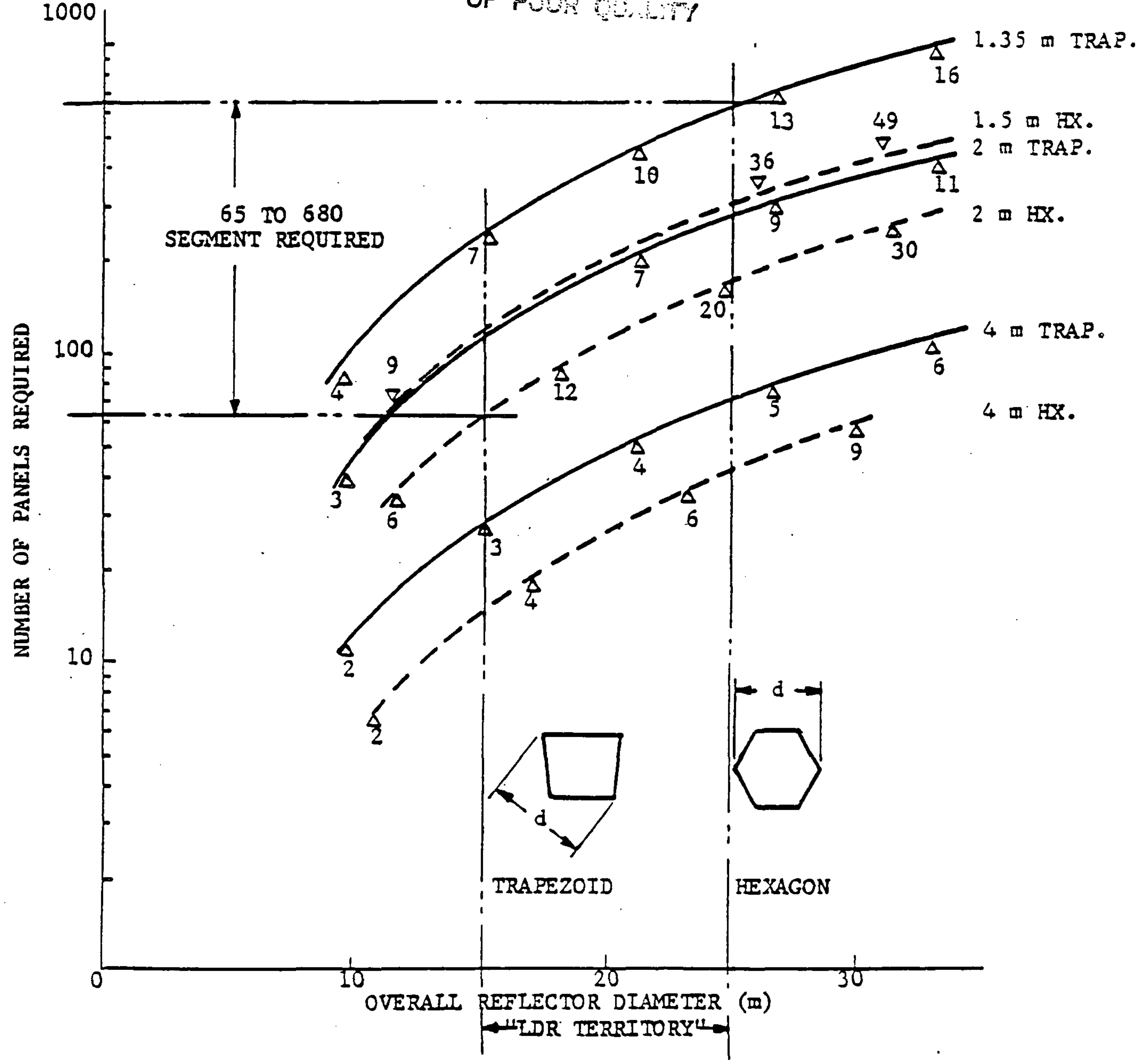


Figure 2-10. Number of Segments and Number of Different Segment Types to Fill an Aperture (Δ_n = Number of Different Figure Types)

In addition, for a given areal density, frequency is inversely proportional to the diameter squared, making 4=d mirrors impractical. It is shown later in Section 4 that the first mode of a 2m, 17kg/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 20kg/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 ($\Delta \overline{T} \simeq 200^\circ F$). 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 1×10^{-10}/°F. This may be too stringent a requirement to expect of even the best materials. On a unit basis, this is equal to 4×10^{-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 16×10^{10}, then the response to a bulk average temperature change would be the same as that of a 6.4mm thin shell whose expansivity diifference is 1×10^{-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 asphericс.
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

		15m				20m				25m			
		f/0.5		f/1		f/0.5		f/1		f/0.5		f/1	
Figure Type		OFF-AXIS PARABOLIC SEGMENTS											
Nominal Radius of Curvature		15m		30m		20m		40m		25m		50m	
		1.5m	2m	1.5m	2m	1.5m	2m	1.5m	2m	1.5m	2m	1.5m	2m
Number Panels Required	HX	112	66	Same		200	120	Same		320	180	Same	
	TRPZ	250	112			440	195			560	290		
Number Different Panels Required	HX	16	9			25	17			36	20		
	TRPZ	7	5			10	7			13	9		
Radius of Curvature Precision, mm± ($\Delta R = 3.46R^2/r^2$, ΔWFrms, and $\Delta WF = 0.5\mu m$)		0.69	0.39	2.77	1.56	1.23	0.69	4.92	2.77	1.92	1.08	7.69	4.33
Corresponding Sagitta Error, mm		0.00087 (32 μinches) →											
Figure Error Allowable		λ /8 rms @ λ = 2 μm →											
Areal Density, kg/m²		39 →				22 →				14 →			
Solid Thickness (h), mm		18 →				10 →				6.4 →			
$\Delta\alpha' \times 10^{-10}$ ($\Delta\alpha' = 3.46\,\Delta WFh/r^2\,\Delta\bar{T}$ and $\Delta WF = 0.8\,\mu m$, $\Delta\bar{T} = 170°F$		5.2	3	5.2	3	3	1.6	3	1.6	2	1	2	1
$\Delta\alpha'$ Applicability (S = Solid, C = Cored Sandwich)		S,C	S,C	S,C	S,C	S,C	C	S,C	C	C	C	C	C

ORIGINAL PAGE IS
OF POOR QUALITY

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.

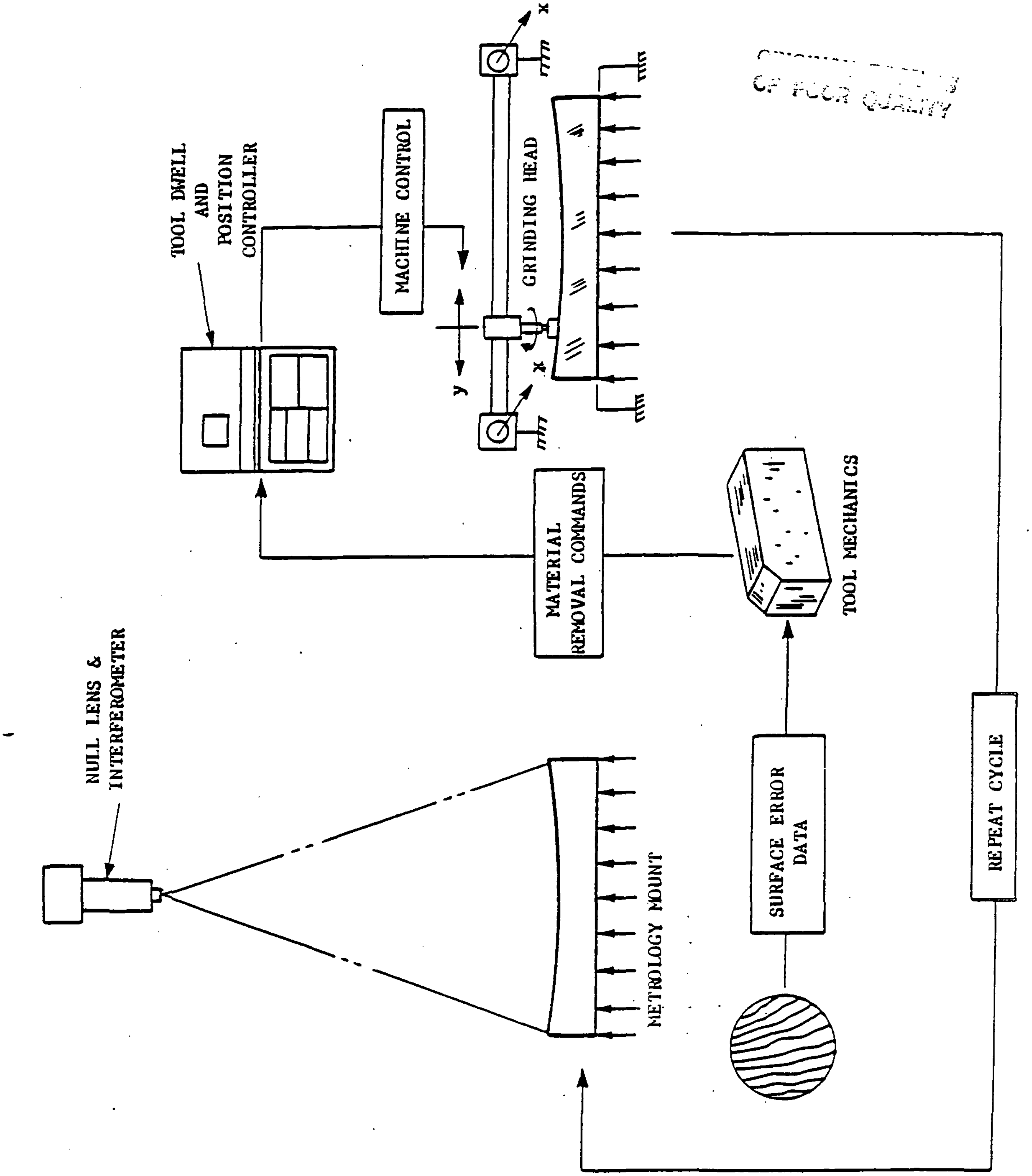


Figure 3-1. Perkin-Elmer Computer Controlled Polisher (CCP) Operation Cycle

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, $\dot{y}$) 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 $\dot{X}$, 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 $\dot{X}$, $\dot{Y}$ 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 difuse 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 $\Delta R/R$ 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 $\Delta\overline{\alpha}$ and $\Delta\alpha'$ 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 3-2
CANDIDATE MATERIALS AND PRODUCIBILITY FACTORS

Candidate Materials	Configuration Applicability				Forming Temp	Frits, Adhesives	Delivery Rate	Current Size Limit	Cost	2µ Perf
	$\Delta\bar{\alpha}$		$\Delta\bar{\alpha}$							
	Solid	Sandwich	Solid	Sandwich						
Heraeus Fused Quartz	-	✓	✓	-	200°C	NO	SLOW	44°	HIGH	YES
Schott Zerodur	-	✓	✓	-	800°C*	YES	FAST	250"	HIGH	YES
Corning Pyrex	-	(✓)	?	-	~	YES	(FAST)	?	LOW	?
Corning "Alumina Silicate"	?	-	-	?	600°C	YES	?	?	?	?
HIP Beryllium	-	-	-	?	~800°C	NO	(FAST)	48"	MODERATE/HIGH	~YES
"Coilzak"/AL.Foam	-	(✓)	-	N/A	RT	YES	FAST	80"	VERY LOW	NO

*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 ΔT equation in the figure. The figure also shows the predicted axial temperature differences that would exist in typical LDR ultralightweight 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 ΔWF 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 ΔT_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

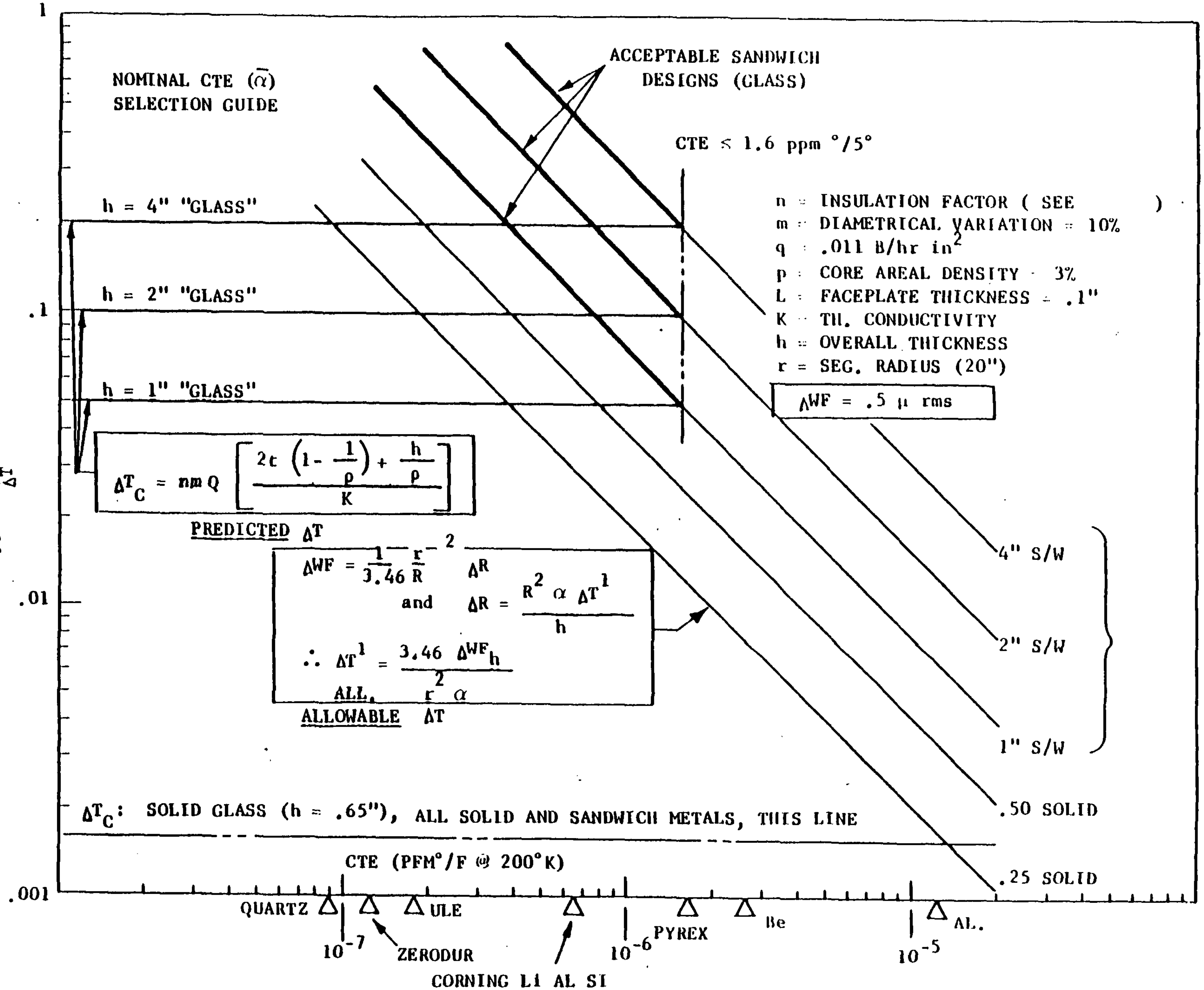


Figure 3-2. Nominal CTE ($\bar{\alpha}$) Selection Guide

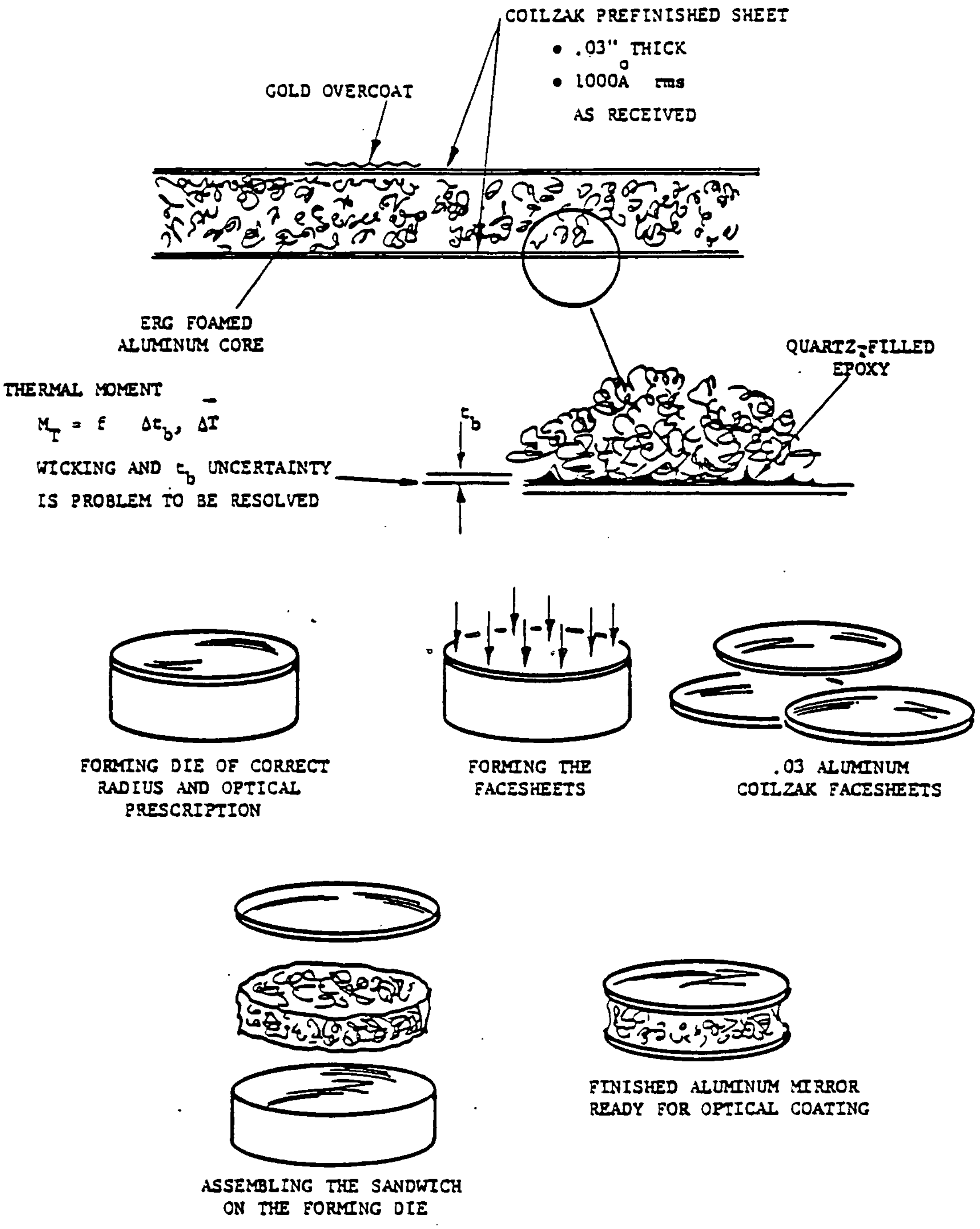


Figure 3-3. The Alcoa Coilzak "Stamped" Metal Mirror Approach

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

$$\Delta WF_{ASTIG} \qquad \frac{r^2(\alpha x - \alpha y)\Delta\bar{T}}{4h}$$

where r and h are the radius and thickness of the panel, respectively. For a maximum wavefront error of 0.5 micrometer rms, $\alpha x - \alpha y$ for a 1.5 cm diameter thin shell cannot exceed 1.3×10^{-10} in/in/°F. For aluminum, whose nominal CTE is 12×10^{-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 $\Delta\alpha$ 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 aereal densities less than 17 or 18kg/m^2. The first mode of a 2m thin shell mirror whose areal density is 18kg/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".

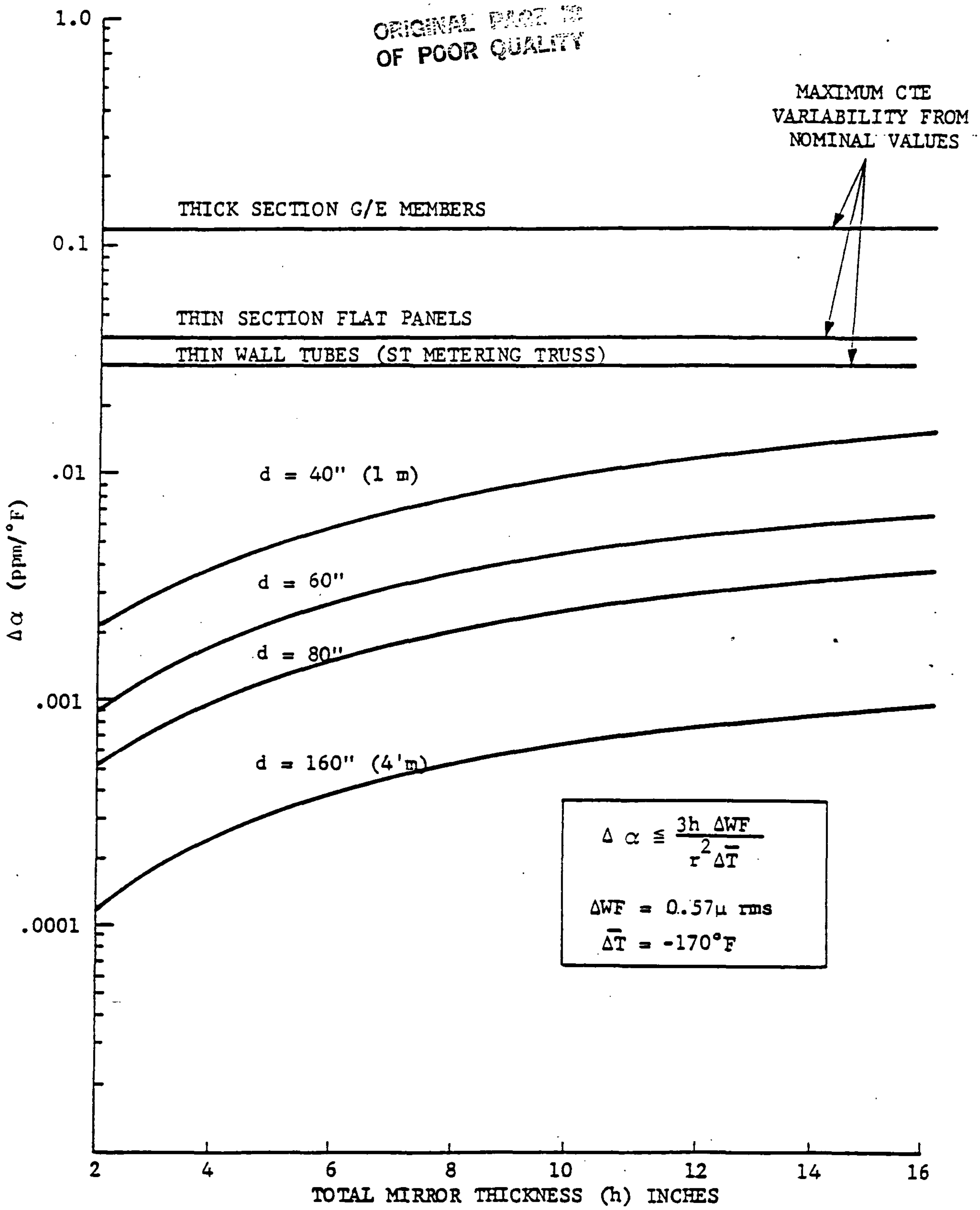


Figure 3-4. Graphite-Epoxy CTE Variability Limits as Applied to LDR Panels

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 S4/t3, 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/in^2, 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/m^2 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

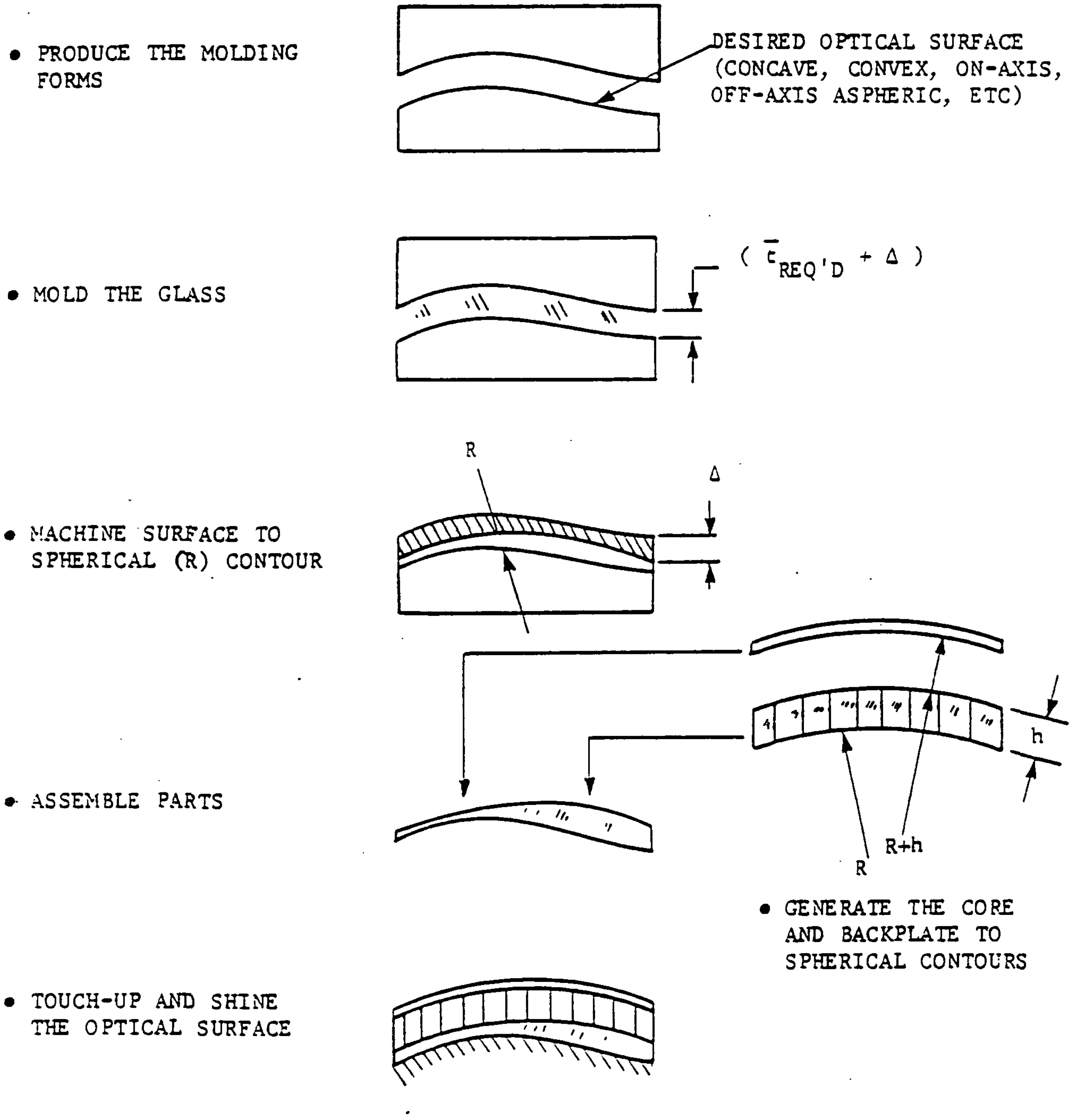
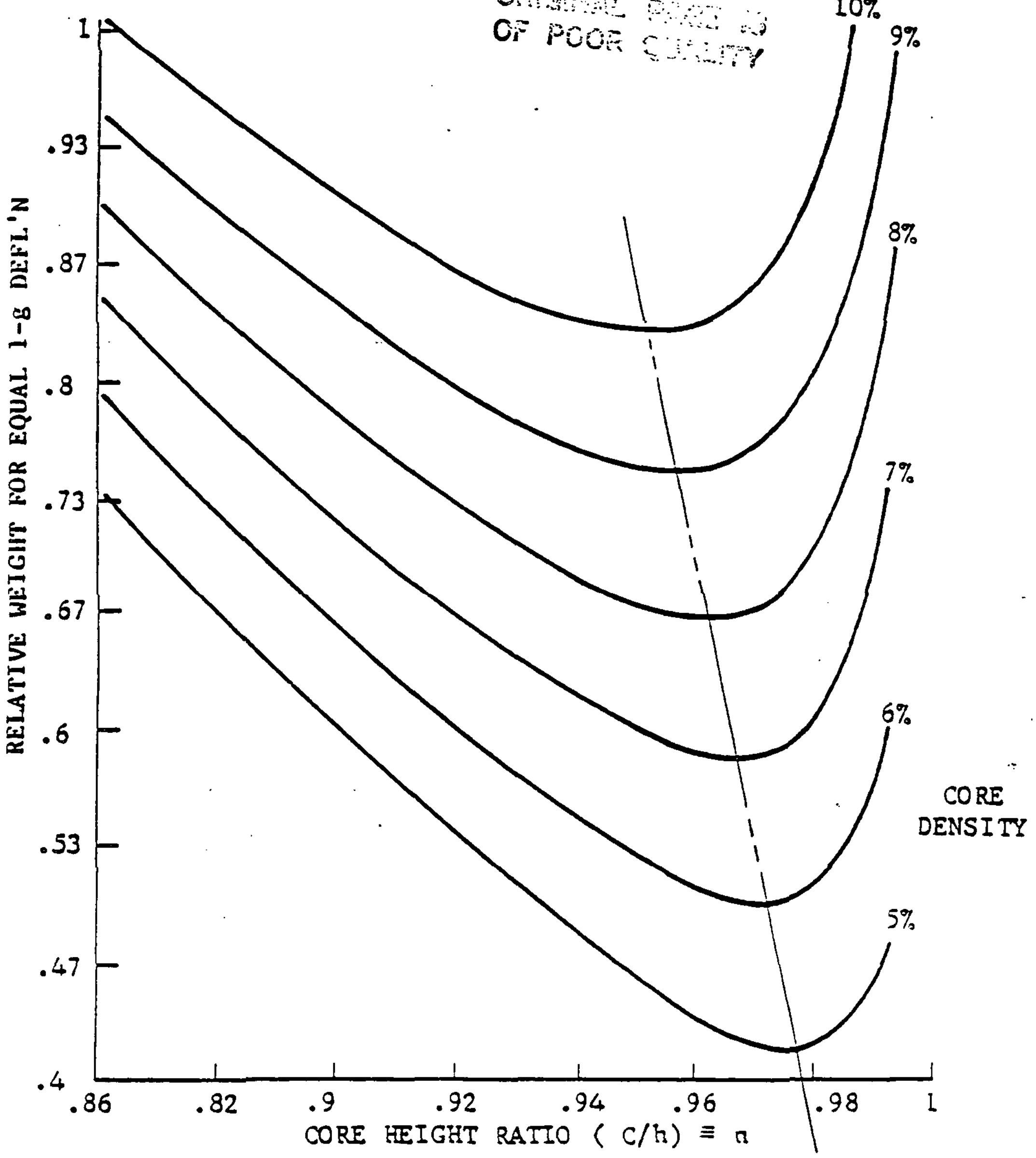


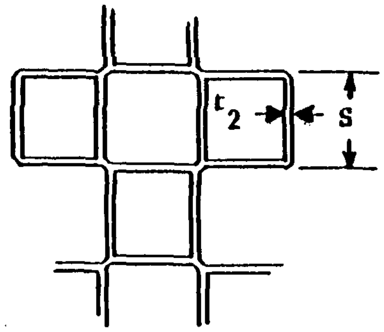
Figure 3-5. How to Make a "Replicated" Sandwich Mirror



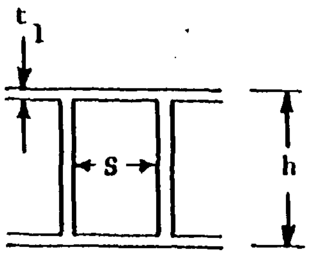
$$W = .229\ \rho D^4 \frac{(1-n+dn)^{1.5}\ [\ (1-\nu^2)\ ]^{.5}}{[\ E\ (1-h^3)\ \Delta\ ]^{.5}}$$

Δ = SPECIFIED DEFLECTION
n = CORE/OVERALL HEIGHT RATIO
d = CORE AREAL DENSITY
ρ = MATERIAL DENSITY
D = MIRROR DIAMETER

Figure 3-6. Mirror Cross Section Optimization



$$\rho_c = \frac{25t_2}{s^2} = \frac{2t_2}{s}$$



$$Q = \frac{S^d}{t_1^3} \; \& \; 2000 < Q < 10{,}000$$

S	$t_2 @ \rho_c = .03$	t_1			OVERALL HEIGHT @ h = 1/.025			ρ_A (Kg/m^2)		
		Q=2000	6000	10,000	Q = 2000	6000	10,000	Q=2000	6000	10,000
1.25	.019	.107	.074	.063	4.28	2.96	2.52	18.7	13	11
1.5	.023	.137	.095	.08	5.4	3.8	3.2	23.8	16.6	14
1.75	.026	.167	.116	.093	6.7	4.6	3.9	29.3	20.2	17
2	.02	.2	.139	.117	8	5.56	4.68			
2.25	.034	.234	.163	.137	9.36	6.52	5.48	35	24.3	20.4
								41	29	24

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

Figure 3-7. Static Deflection for a Family of Ultralightweight Mirrors

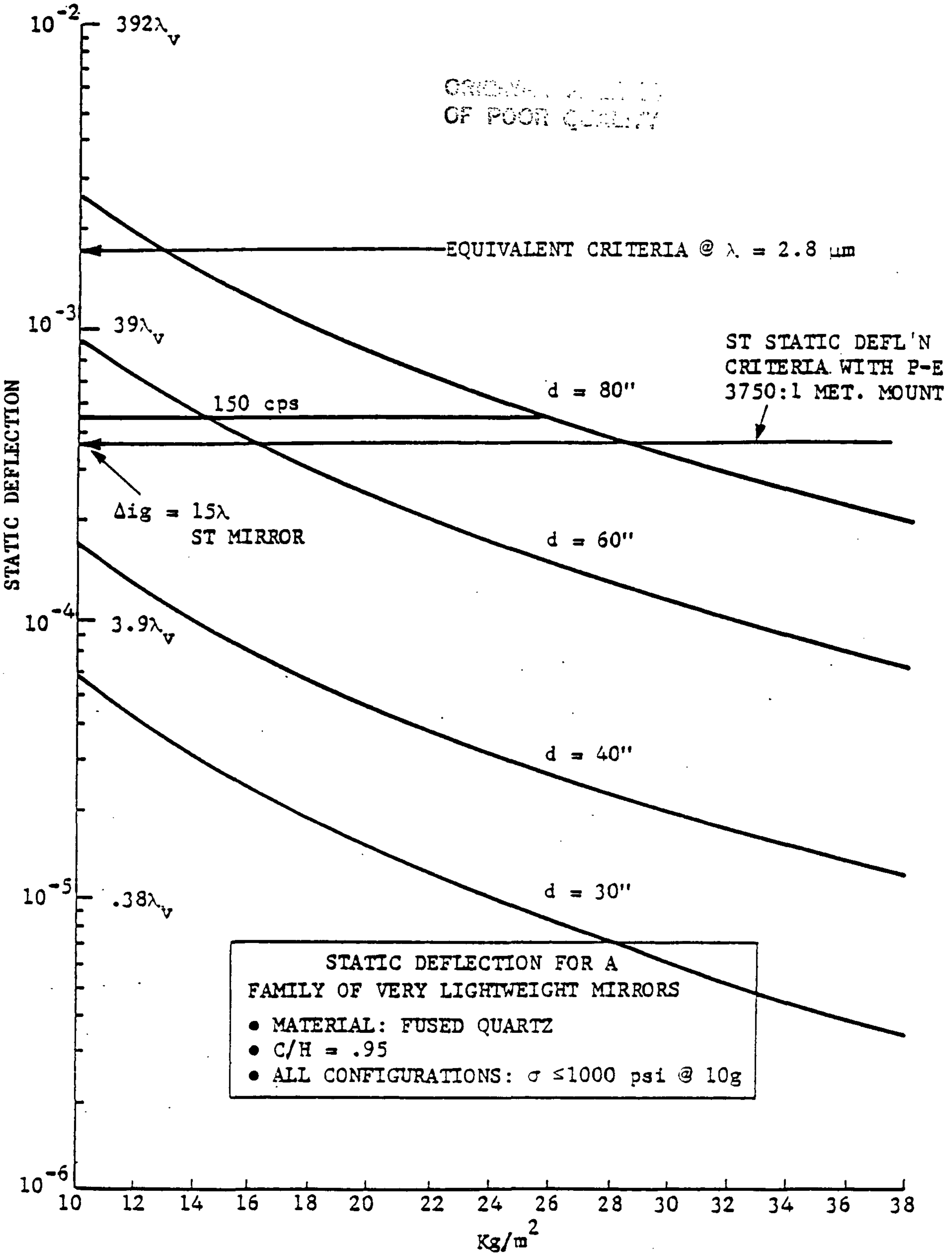


Figure 3-8. Static Deflection for a Family of Ultralightweight Mirrors (Material is fused quartz; c/h=0.95; for all configurations $\sigma \leq$ 1000 psi @ 10g)

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:

$$\Delta_{1g} \leq 2.8/250 \times 3750 \times (39.37 \times 10^{-6}) = 0.0017 \text{ inches}$$

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.

SECTION 4

IDENTIFICATION AND EVALUATION OF PRIME TECHNOLOGIES

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 Δ 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

TECHNOLOGY ISSUES	CANDIDATE MATERIALS			
	GLASSES	GLASS/CERAMICS	METALS	COMPOSITES
<u>PERFORMANCE</u>				
DIMENSIONAL STABILITY	●	●	◐	○
HOMOGENEITY	●	◐	◐	○
POLISHABILITY	●	●	◐	○
AVAILABILITY/DELIV. RATES	○	◐	○	●
<u>FABRICATION</u>				
FORMABILITY/REPLICATION	○	○	◐	●
JOINING	●	◐	●	●
SHAPING AND FIGURING "SPEED"	◐	◐	◐	●
FACILITIES	◐	●	○	●
LIGHTWEIGHTING	◐	○	◐	●
METROLOGY	◐	◐	◐	●
MOUNTING	○	○	◐	◐

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

Figure 4-1. Candidate Materials

ORIGINAL PAGE IS
OF POOR QUALITY

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 $\Delta\alpha'$ 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 1500°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 $\Delta\alpha'$ 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 assessinq 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 wave = 30 micrometers or 0.35 wave at wave = 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 saggita of a 2m panel employed in a 20m, f/.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.

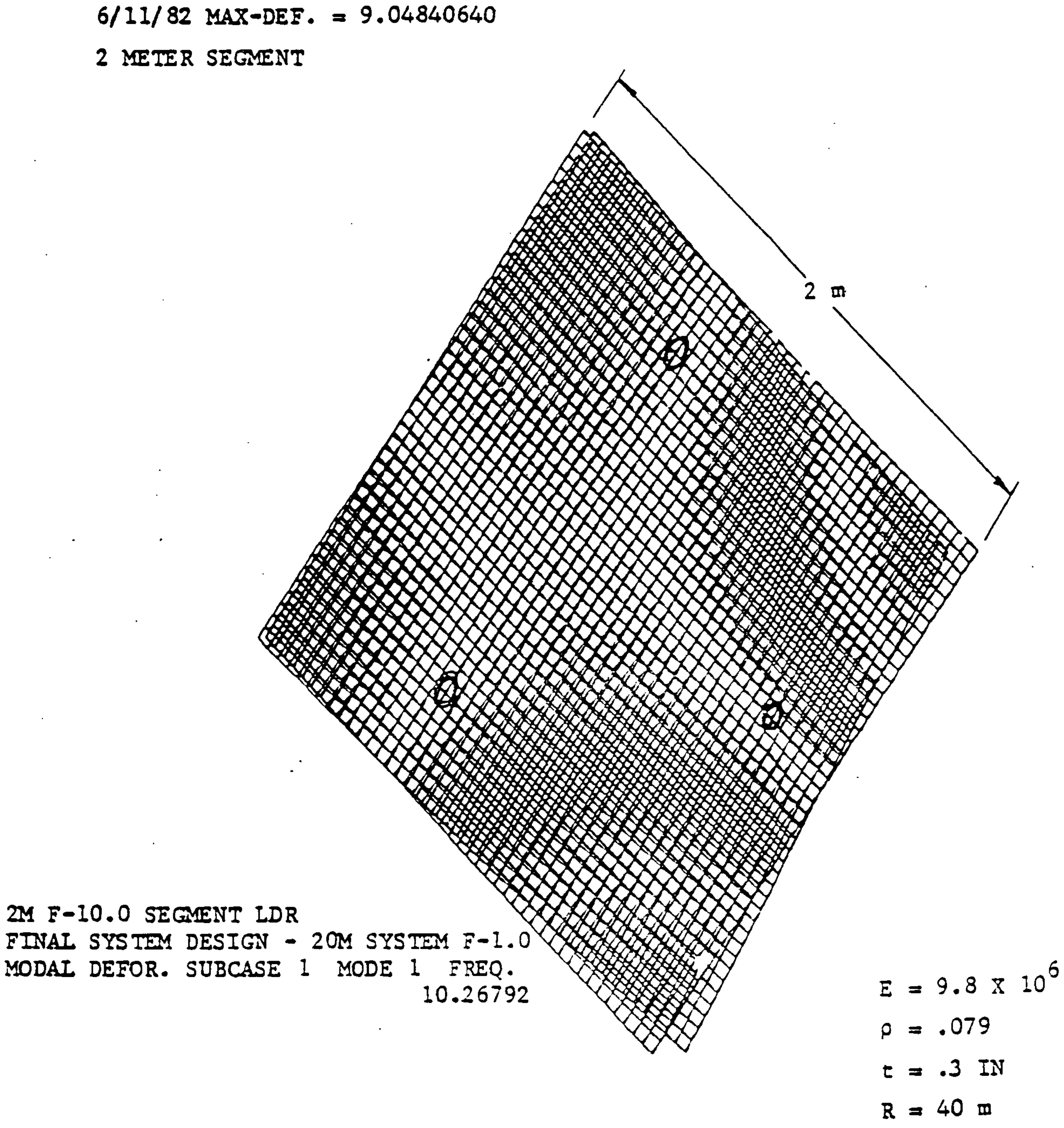
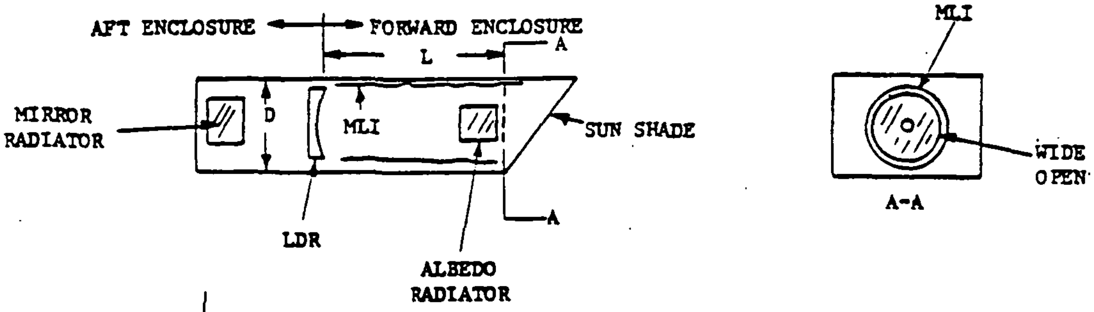
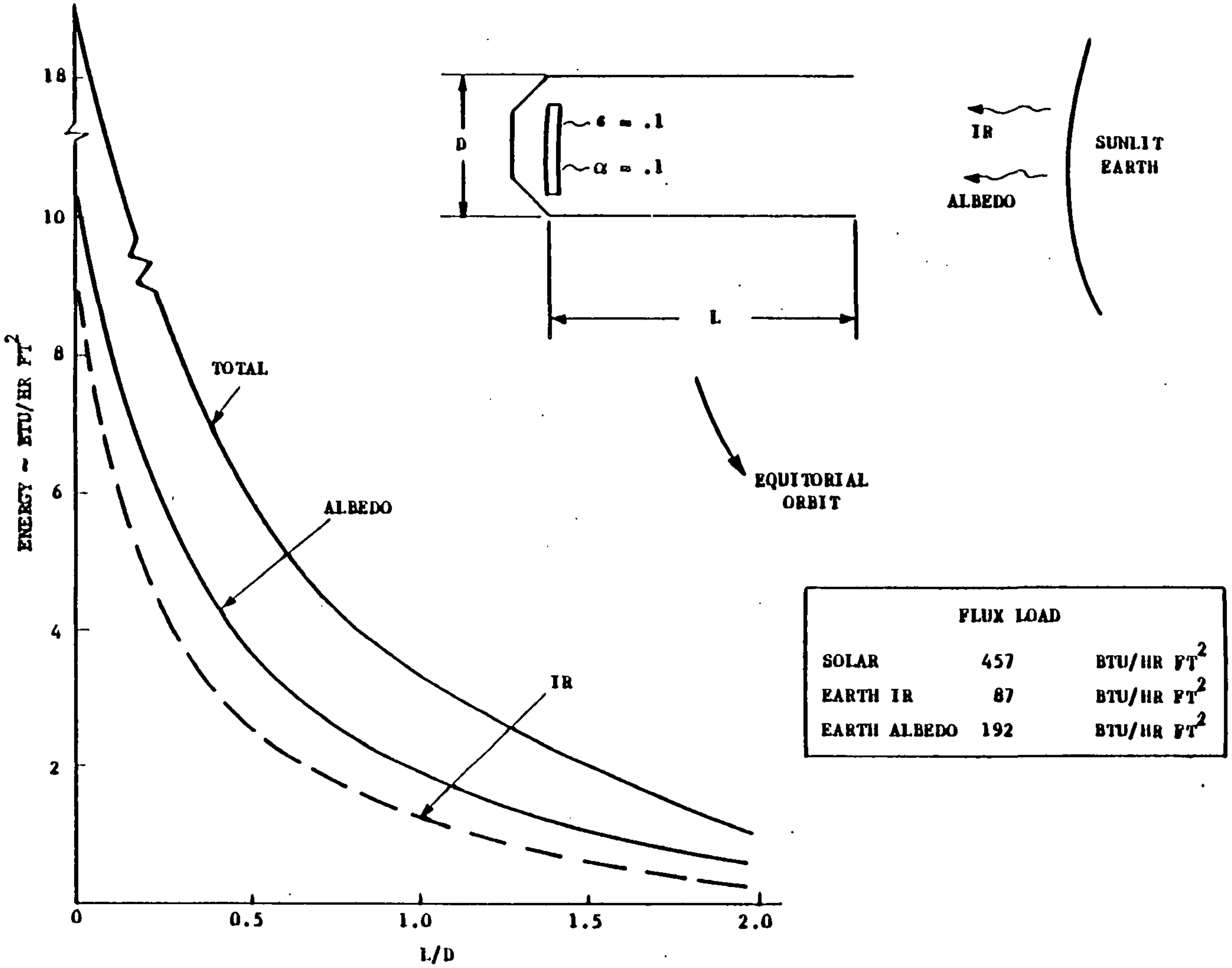


Figure 5-1. Support Moved Inboard Resulted in a Nearly 2X Frequency Increase



PARAMETER	
FORWARD ENCLOSURE LENGTH (L)	CONTROLS ENERGY IRRADIATING/ABSORBED BY THE LDR
ENCLOSURE MLI	MINIMIZES SIDE TO SIDE GRADIENTS WITH MLI MAXIMUM GRADIENT CHANGE < 1°F
RADIATOR RADIATOR/SHADE	PROVIDES AN AREA FOR EARTH IR AND ALBEDO ENERGY REJECTION
SUN SHADE	ELIMINATES THE POSSIBILITY OF THE SUN IRRADIATING THE INTERIOR OF THE FORWARD ENCLOSURE
MATERIAL ABSORBTIVITY (α) EMISSIVITY (ϵ)	THERMAL RADIATION PARAMETERS • EXTERNAL ENCLOSURE $\alpha/\epsilon = .2/.8$ • LDR $\alpha/\epsilon = .1/.1$ • INTERNAL ENCLOSURE $\alpha/\epsilon = .8/.8$

Figure 5-2. LDR Enclosure Design Concept



FLUX LOAD		
SOLAR	457	BTU/HR FT^2
EARTH IR	87	BTU/HR FT^2
EARTH ALBEDO	192	BTU/HR FT^2

Figure 5-3. Maximum Energy Absorbed by the Reflector

TABLE 5-1
LDR ENCLOSURE TEMPERATURE

- FORWARD ENCLOSURE TEMPERATURE

Configuration/Temperature ∿ °F

	Maximum	Minimum	Average
No Radiator	83	-460	-145
Albedo Radiator	44	-225	-114
Moveable Shade	-105	-127	-120

- AFT ENCLOSURE TEMPERATURE

Configuration/Temperature ∿ °F

	Maximum	Minimum	Average
No Radiator	83	-460	-145
Albedo Radiator	-105	-127	-120
Moveable Shade	-460	-460	-460

- ABSORBED ENERGY

Maximum 1.5 BTU/hr - ft^2
Side-to-side variation $\underset{-}{\sim}$ 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 1°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 ft^2°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:

$$\frac{M_1}{M_o} = 1 \frac{4(I_{(1,0)}\ I_{(0,0)})}{\text{Strehl}}$$

where

$$I_{(1,o)}/I_{(o,o)} = \frac{\pi^2\sigma^2}{1-2\pi^2\sigma^2}$$

and

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

and where

σ is the rms WF error, equal to the quilt amplitude divided by two, and

M_1/M_o 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 x 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.

SECTION 6

DESIGN DEFINITION AND CONCEPT SELECTION

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 $\Delta\alpha'$ criterion. Quartz, in sandwich form, is undoubtedbly 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

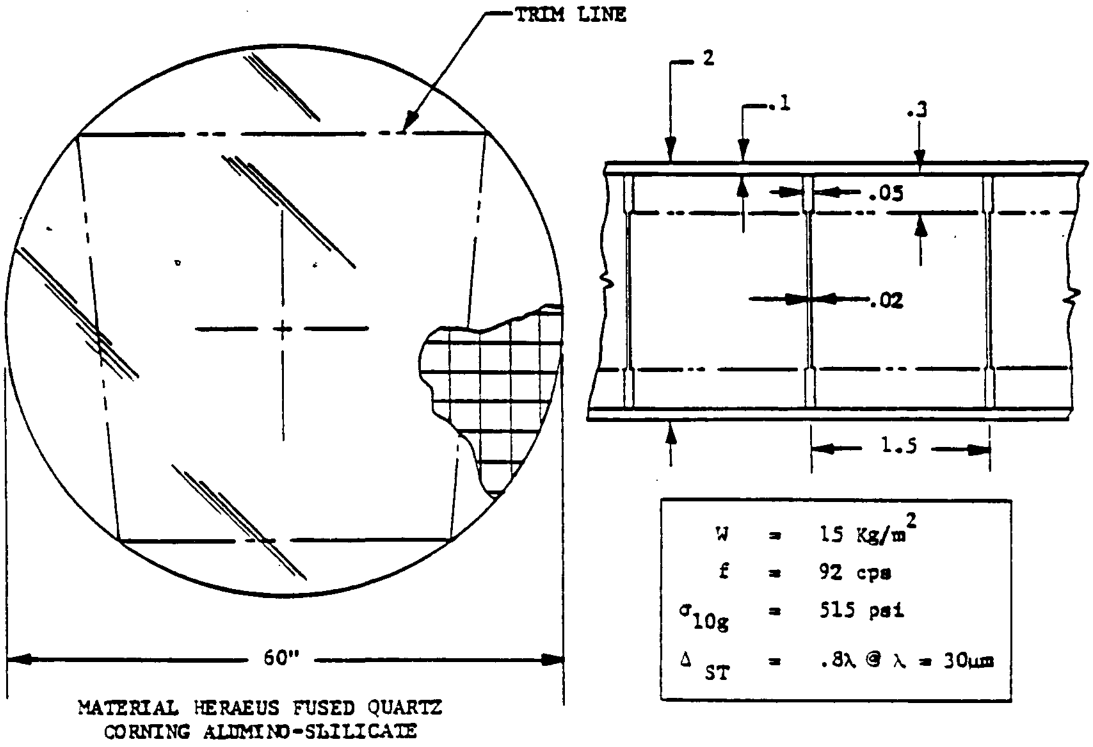


Figure 6-1. Optimal LDR Mirror Panel

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 1:4X 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 19kg/m^2, still acceptably light for an LDR reflector.

6.3 QUILTING AVOIDANCE TECHNIQUE

With these mirrors, we are dealing with quilting susceptibility values, S4/t3, of $\overset{\sim}{5000}$. 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

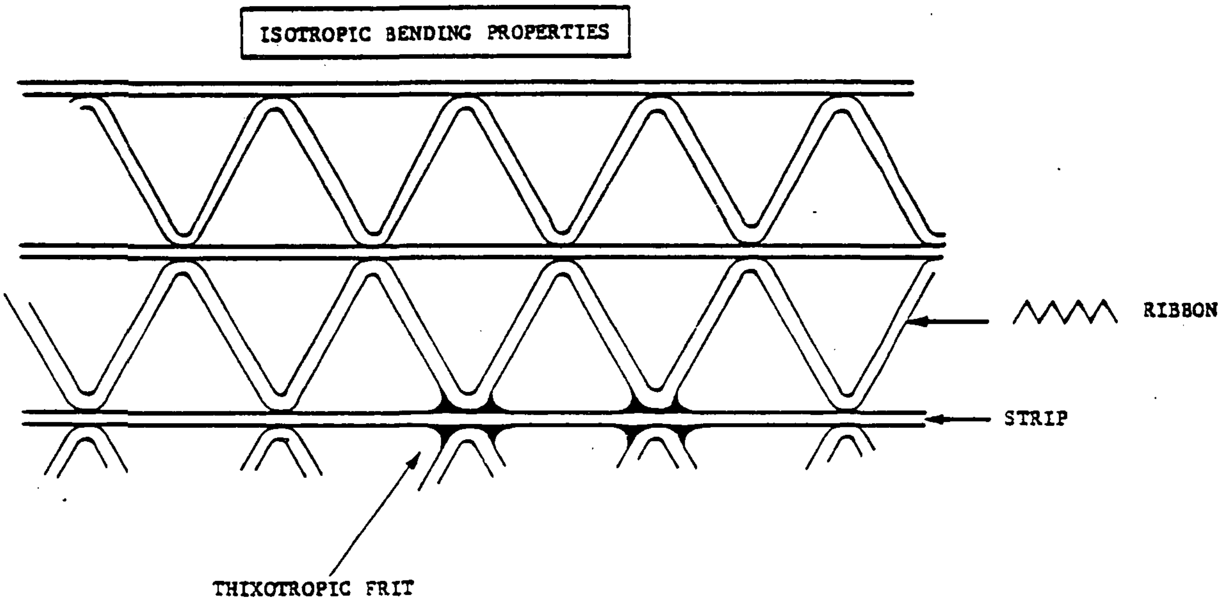
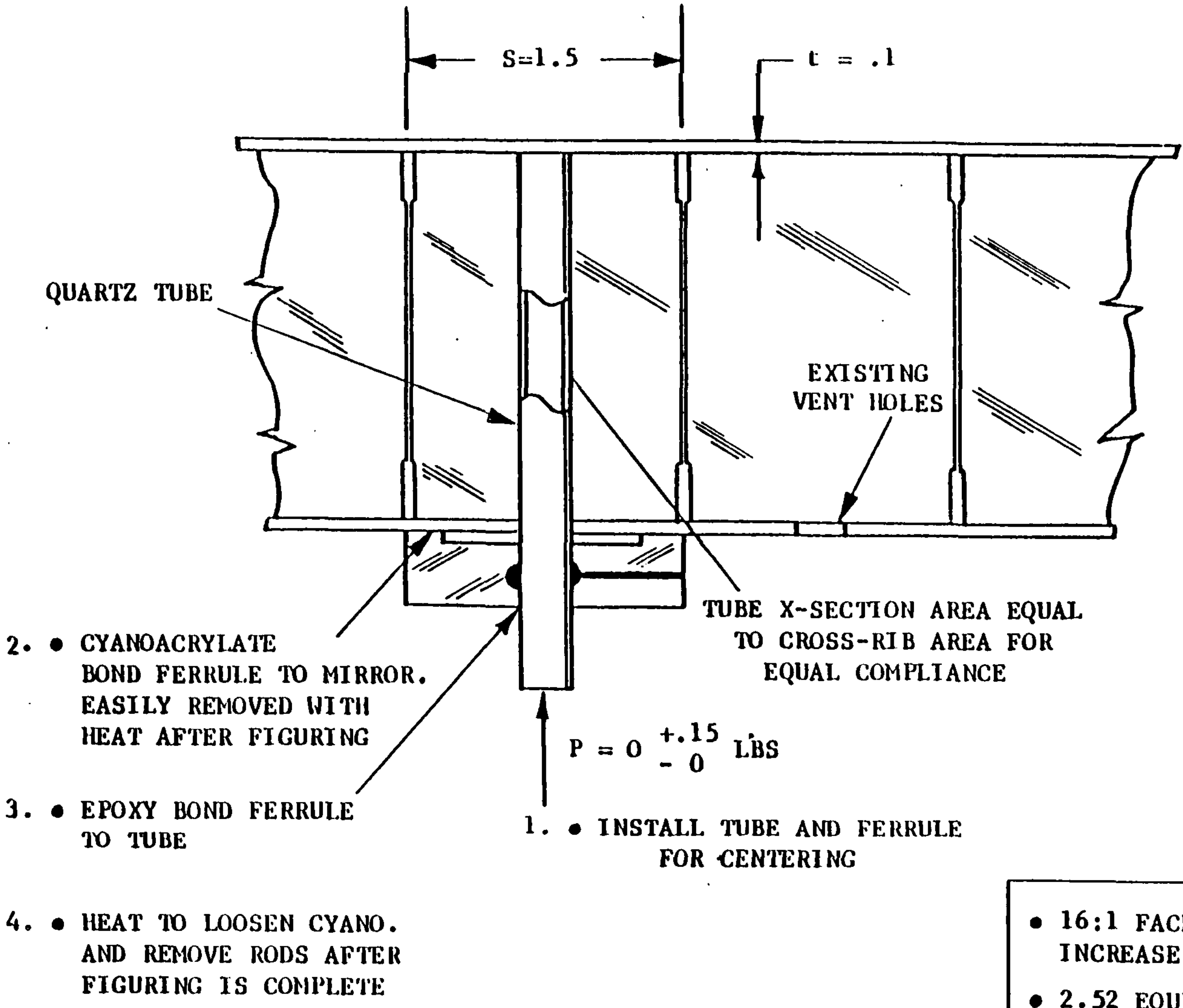


Figure 6-2. Pyrex Ribbon Core Mirror Construction, Feasible by Virtue of Pyrex's Highly Formable Nature



1. • INSTALL TUBE AND FERRULE FOR CENTERING

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

- 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 4×10^{-6} 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 impoved 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.

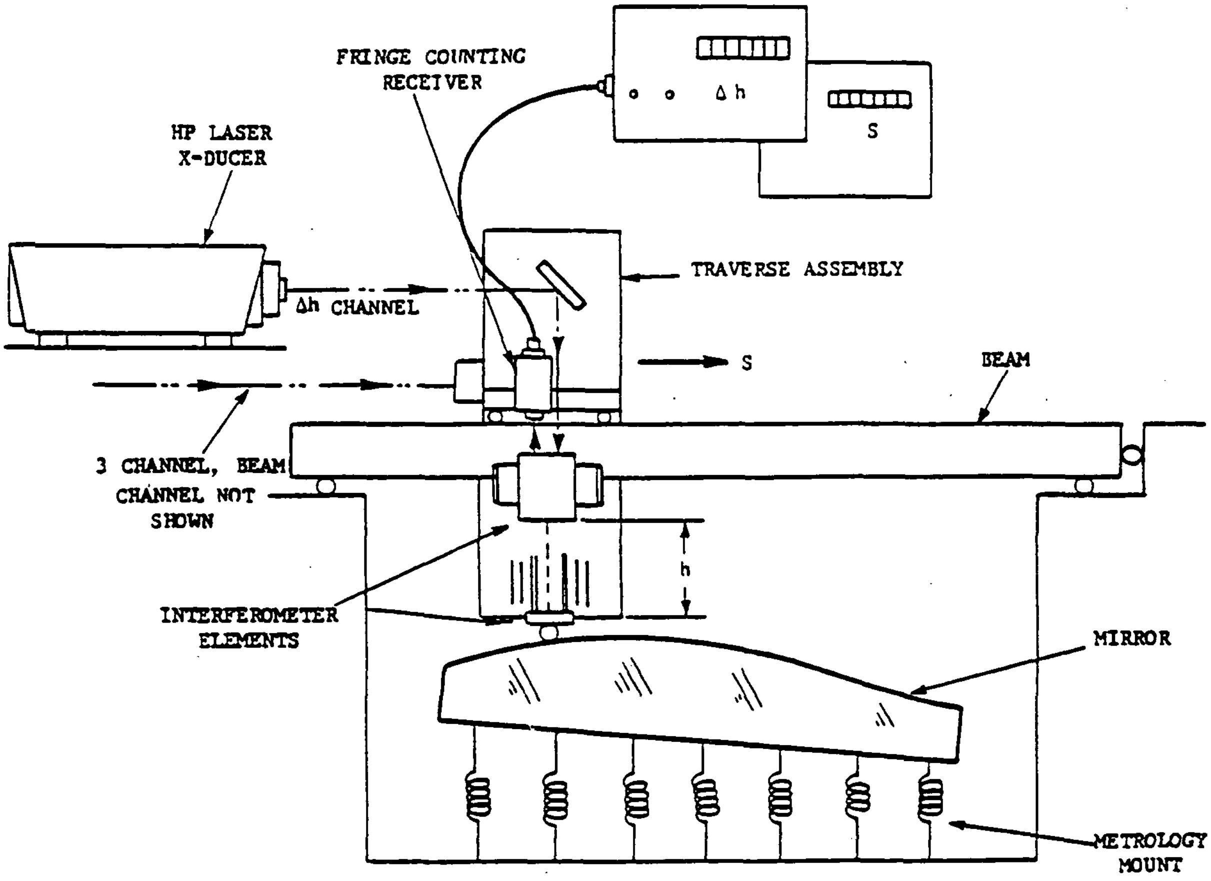


Figure 6-4. Contour Sensing of Non-Symmetric Convex Aspheric Optical Surfaces

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 ultralightweight, 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

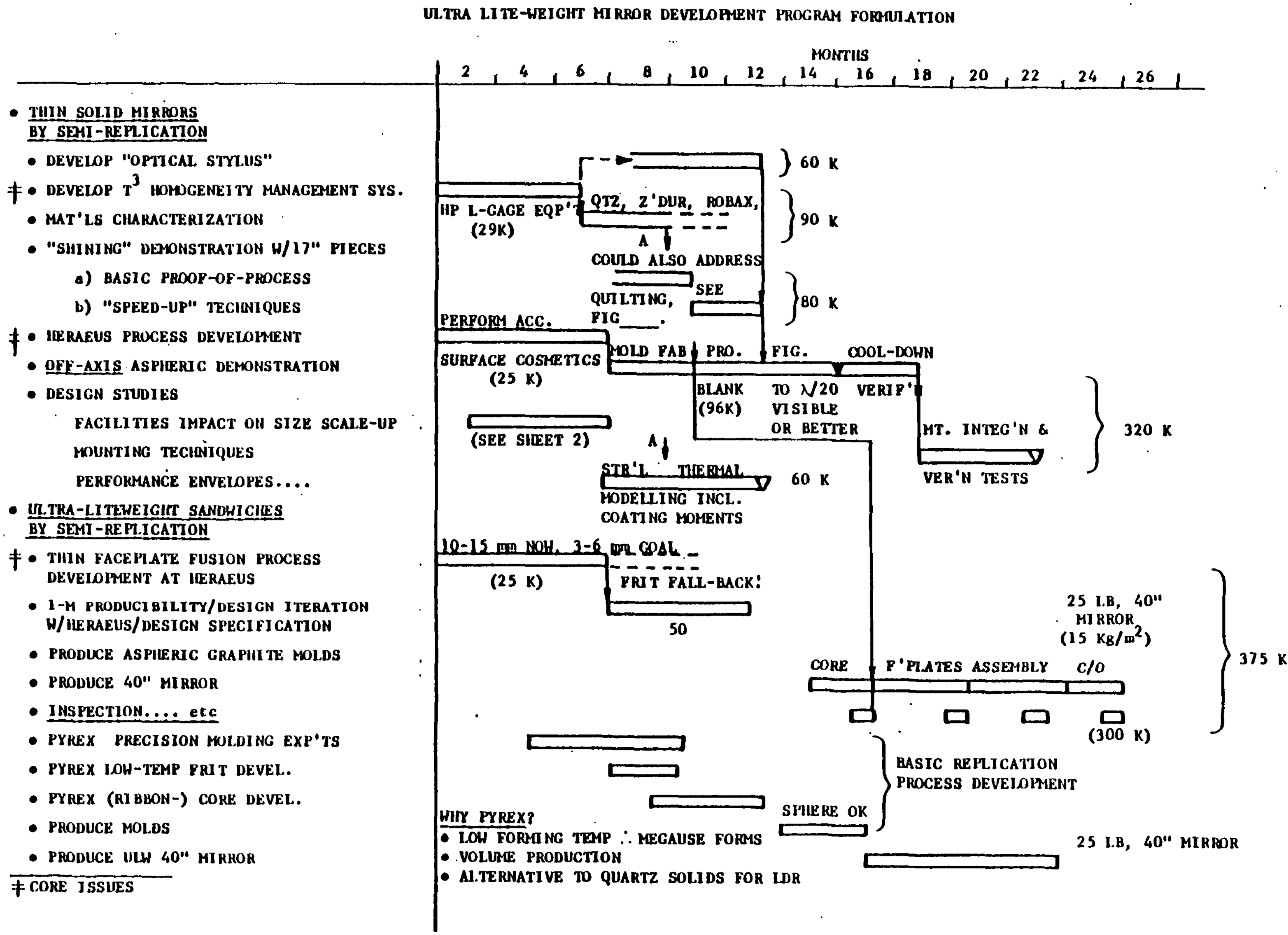
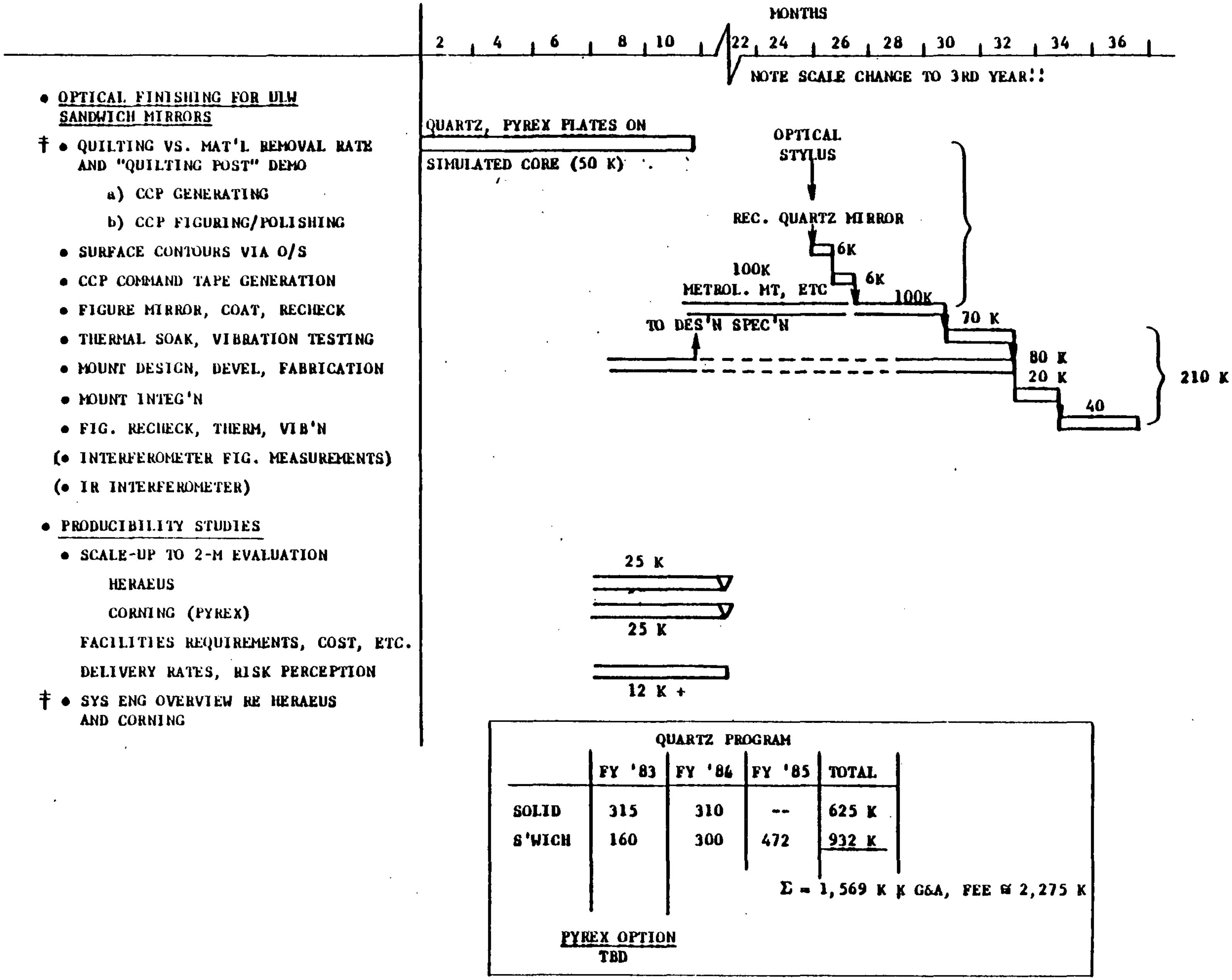


Figure 7-1. Ultralightweight Mirror Development Program Formulation (Sheet 1 of 2)



QUARTZ PROGRAM

	FY '83	FY '84	FY '85	TOTAL
SOLID	315	310	--	625 K
S'WICH	160	300	472	932 K

Σ = 1,569 K K G&A, FEE ≅ 2,275 K

PYREX OPTION
TBD

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 $\Delta\alpha'$ 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 appartus 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 fundemental 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

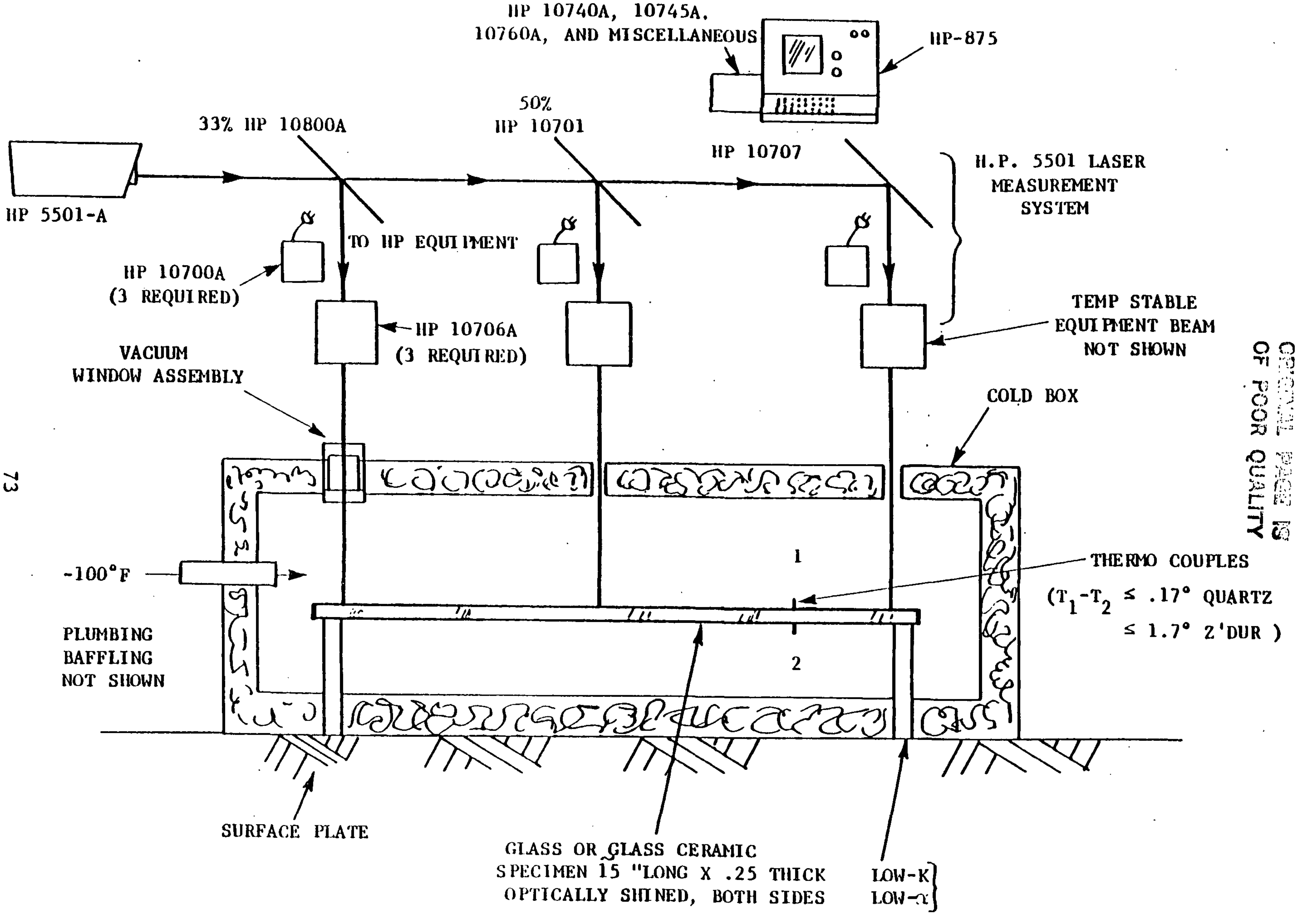


Figure 7-2. Apparatus for Thru-the-Thickness CTE Measurements

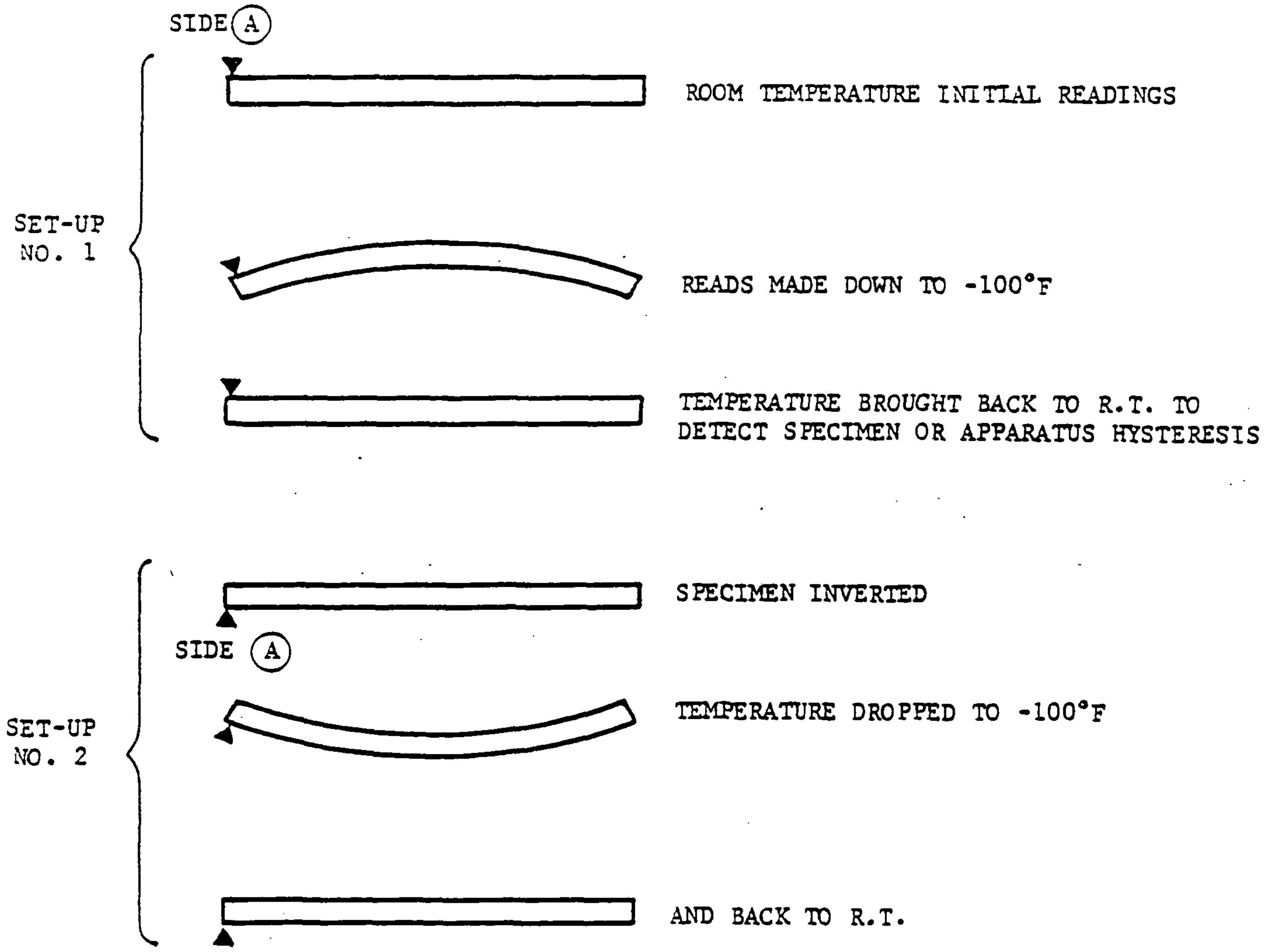


Figure 7-3. Experiment Sequence

ORIGINAL PAGE IS
OF POOR QUALITY

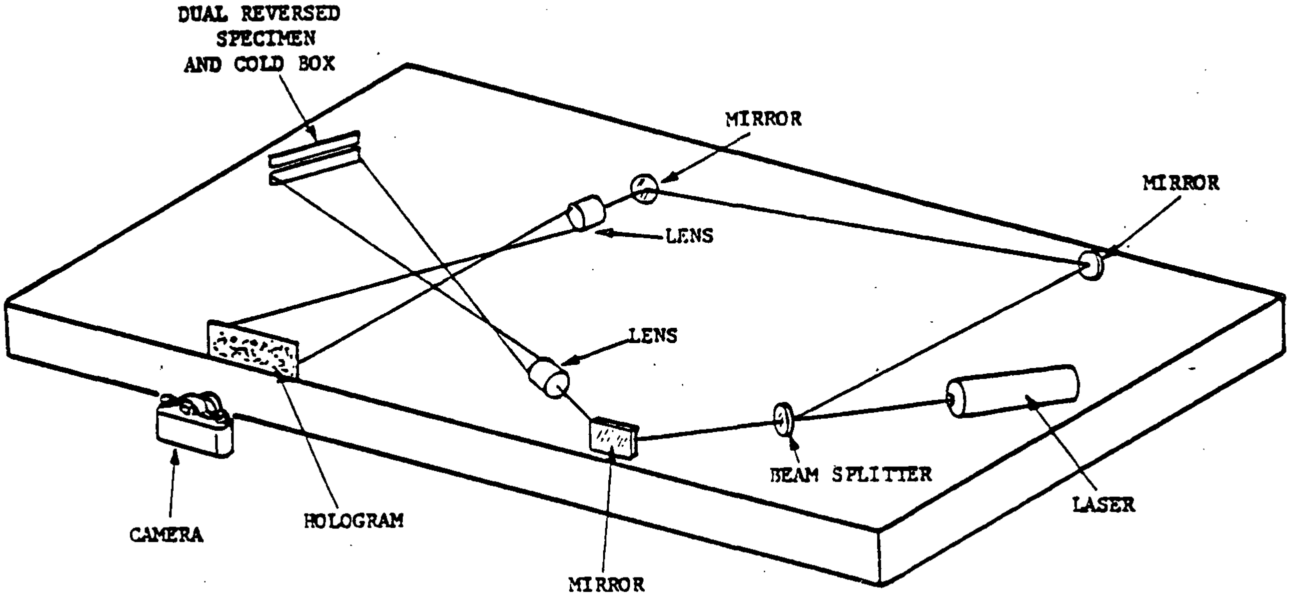
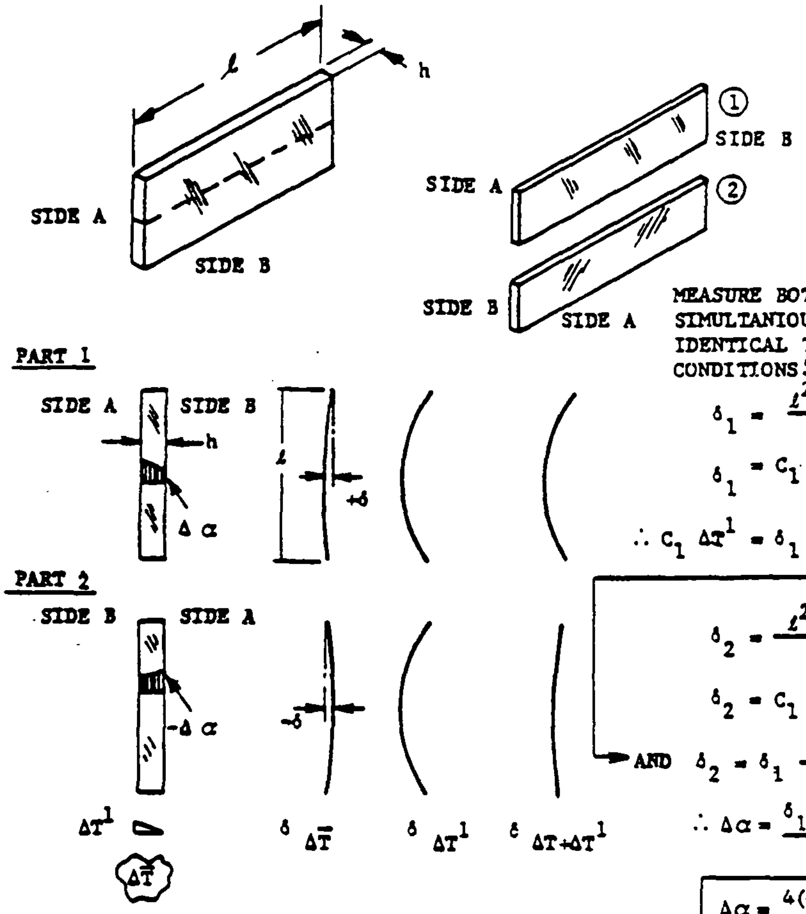


Figure 7-4. Alternative Measurements Concept #1 (Sheet 1 of 2)



HOW TO KEEP THE INFLUENCE OF AXIAL TEMPERATURE GRADIENTS (ΔT^2) FROM FOULING UP THE DATA.

MEASURE BOTH PARTS SIMULTANIOUSLY i.e. IDENTICAL THERMAL CONDITIONS!!

$$\delta_1 = \frac{\ell^2 \alpha \Delta T^1}{8h} + \frac{\ell^2 \Delta\alpha \Delta\bar{T}}{8h}$$

$$\delta_1 = C_1 \Delta T^1 + C_2 \Delta\alpha$$

$$\therefore C_1 \Delta T^1 = \delta_1 - C_2 \Delta\alpha$$

$$\delta_2 = \frac{\ell^2 \alpha \Delta T^1}{8h} - \frac{\ell^2 \Delta\alpha \Delta\bar{T}}{8h}$$

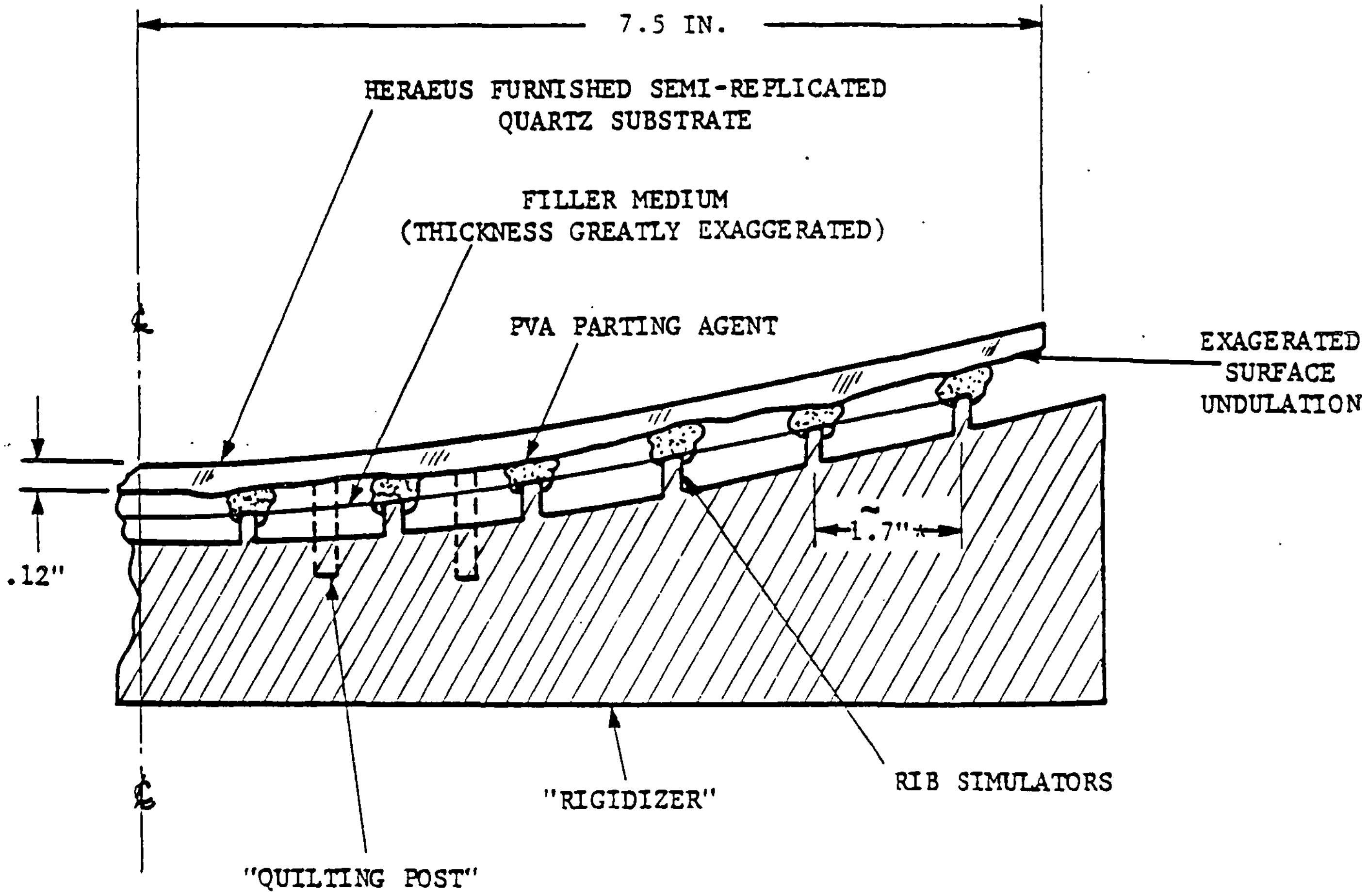
$$\delta_2 = C_1 \Delta T^1 - C_2 \Delta\alpha$$

AND $\delta_2 = \delta_1 - C_2\Delta\alpha - C_2\Delta\alpha$

$\therefore \Delta\alpha = \dfrac{\delta_1 - \delta_2}{2C_2}$ AND $C_2 = \dfrac{\delta^2 \Delta\bar{T}}{8h}$

$$\boxed{\Delta\alpha = \frac{4(\delta_1 - \delta_2)}{\ell^2 \Delta\bar{T}}}$$

Figure 7-4. Alternative Measurements Concept #1 (Sheet 2 of 2)



* s^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 procurred. 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 Heraues. 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 ømirror of about 15 to $20 kg/m^2$.

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.

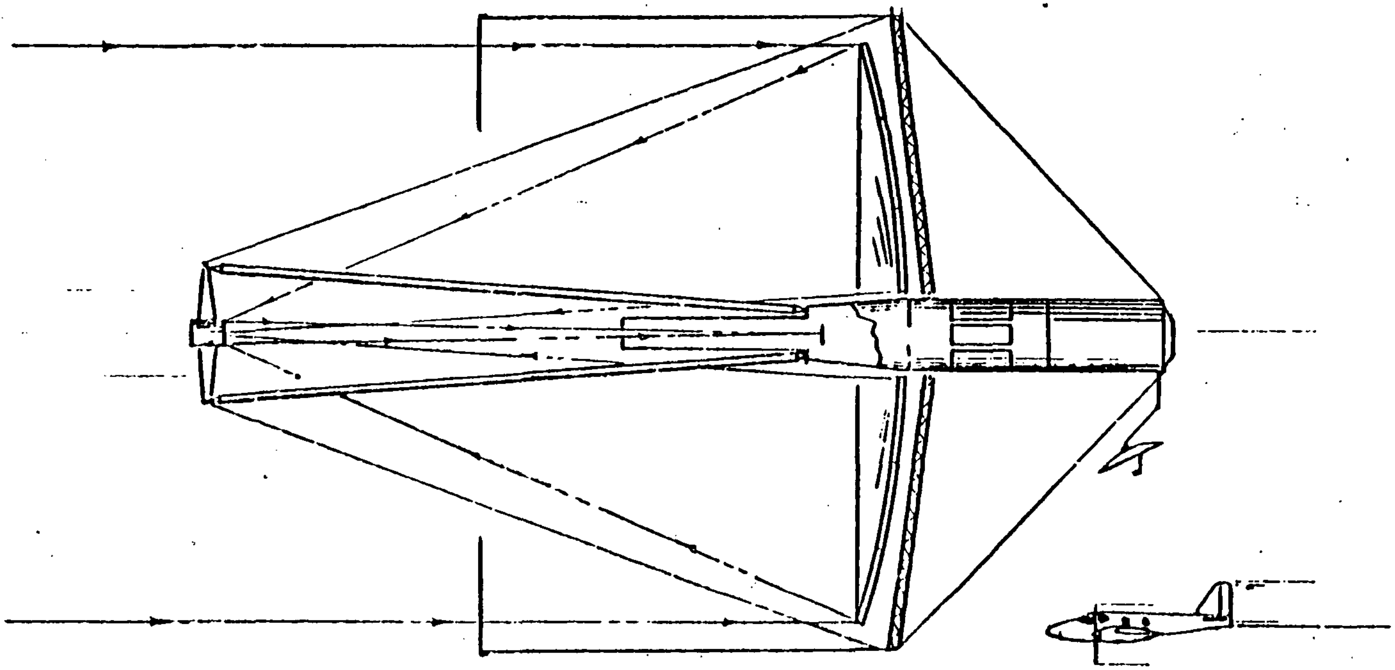
LDR
SEGMENT TECHNOLOGY ASSESSMENT STUDY

FIRST BRIEFING

APPENDIX A

FIRST BRIEFING

ORIGINAL



LDR

SEGMENT TECHNOLOGY ASSESSMENT STUDY

FIRST BRIEFING 10/15/81

PERKIN-ELMER
OTD

10/11/81

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

STUDY

OBJECTIVES

OVERVIEW

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

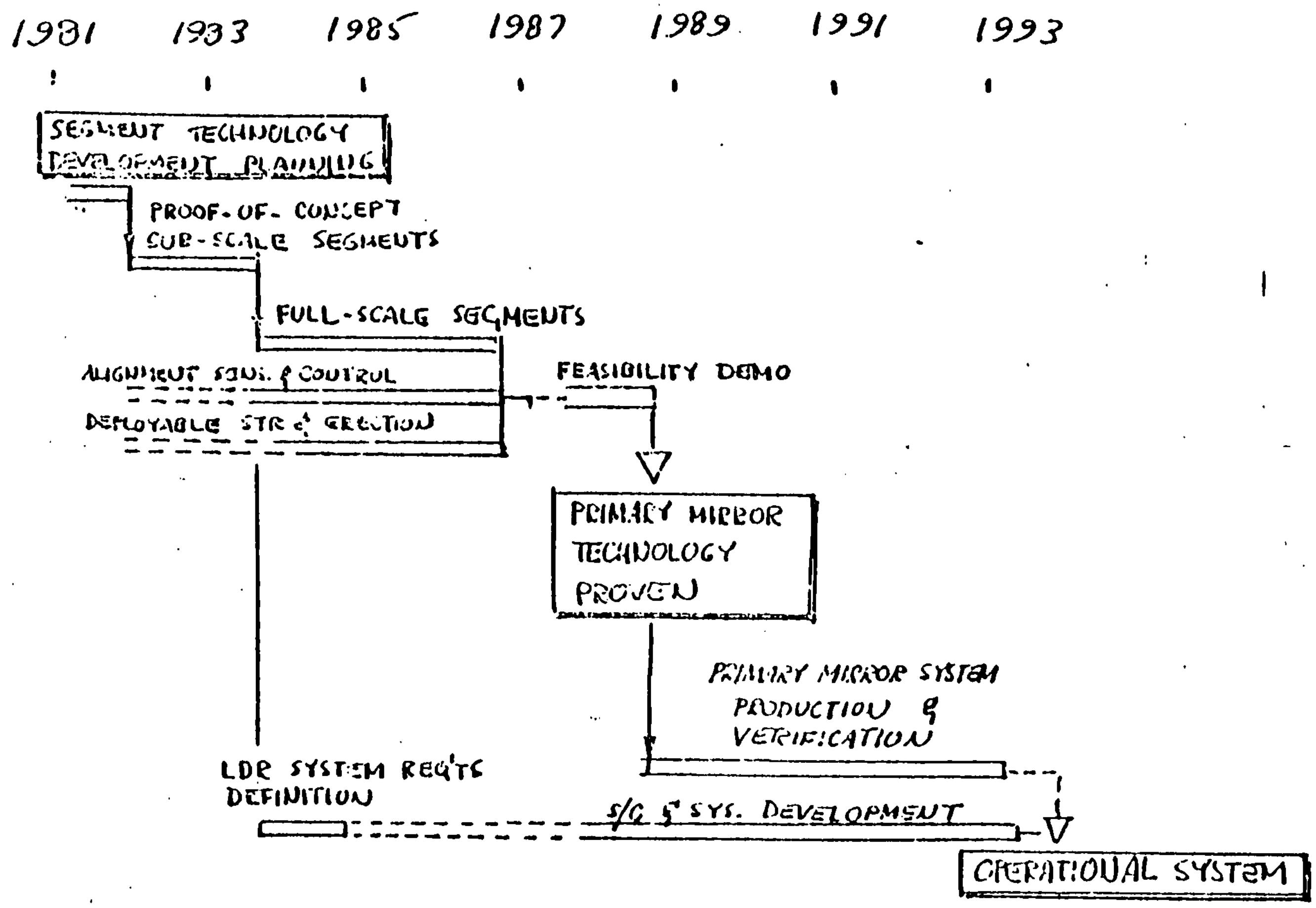
TOP LEVEL LDR REQUIREMENTS

(FROM SOW & ATTACHMENTS)

OVERALL DIA.	$10 \leq D \leq 30$ M
FIGURE TYPE	PARABOLA OR HYPERBOLA/NOT SIMPLY SPHERICAL
FIGURE QUALITY	D/L @ 30 $\mu \rightarrow \frac{\lambda}{13.7}$ RMS OR $\left. 2.2\ \mu \right]_{\text{SYSTEM}} \longrightarrow 2\ \mu_{\text{RMS}}$ MIRROR
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

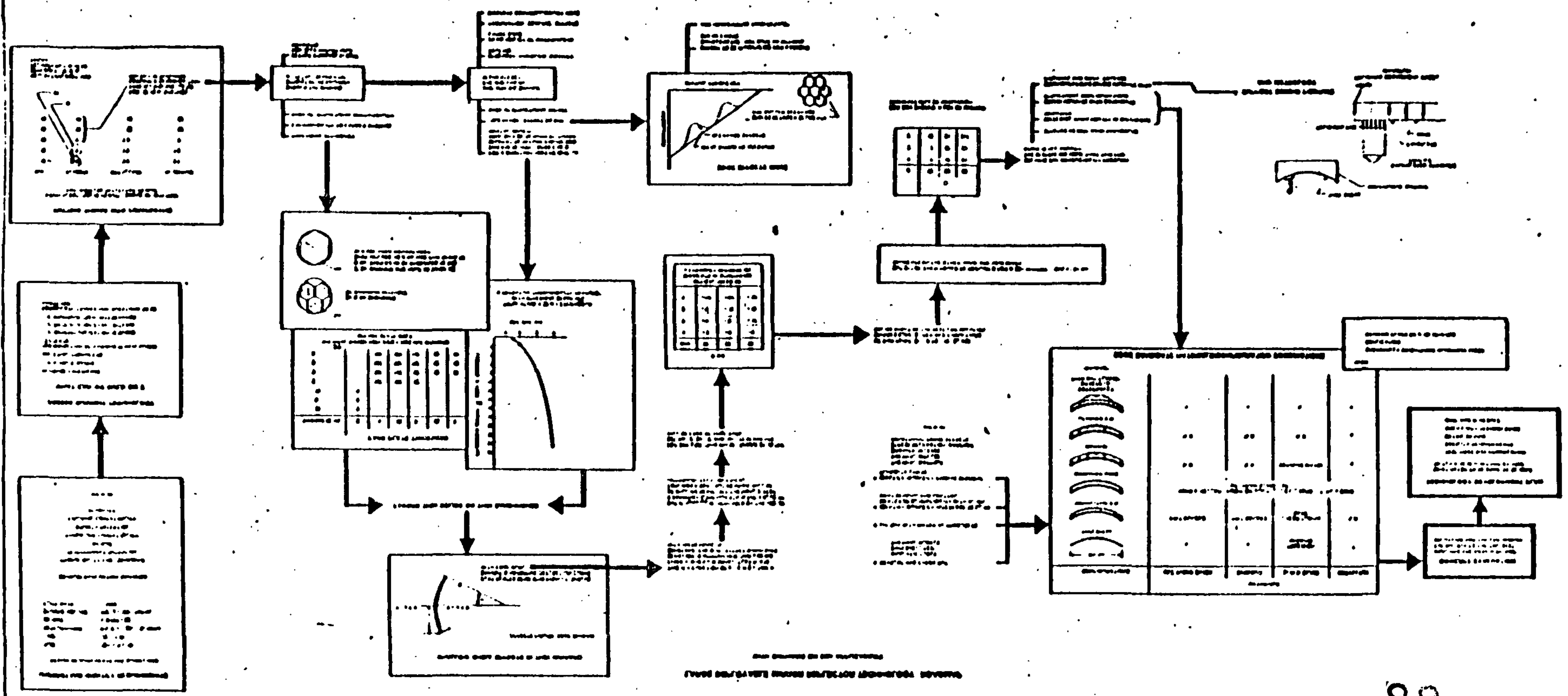
10/15/81 MK

OVERALL LDR PROGRAM MILESTONES



30m 2-1000 m
ASTRONOMICAL RESEARCH
INSTRUMENT

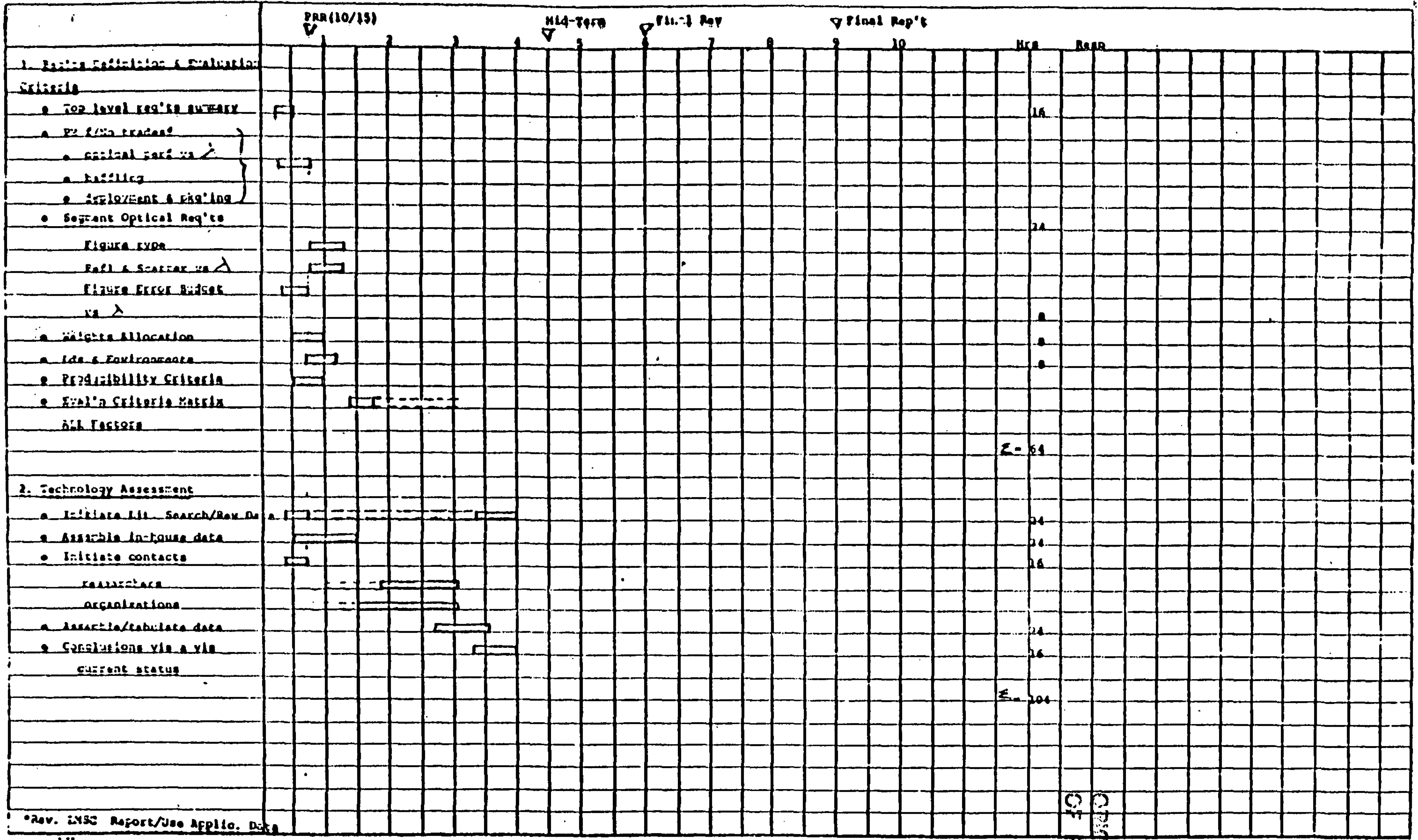
10/15/81 MK



TECHNOLOGY ROADMAP
~ Pls. refer to handout ~

STER PLANNING FORM
– MONTHLY –

10/5/81



	Hrs	Resp
1. Baseline Definition & Evaluation Criteria		
• Top level req'ts summary	16	
• PM f/No trades*		
• optical perf vs λ		
• baffling		
• deployment & pkg'ing		
• Segment Optical Req'ts	24	
Figure type		
Refl & Scatter vs λ		
Figure Error Budget vs λ	8	
• Weights Allocation	8	
• Lds & Environments	8	
• Producibility Criteria		
• Eval'n Criteria Matrix All Factors		
	Σ = 64	
2. Technology Assessment		
• Initiate Lit. Search/Rev Data	24	
• Assemble in-house data	24	
• Initiate contacts	16	
researchers		
organizations		
• Assemble/tabulate data	24	
• Conclusions vis a vis current status	16	
	Σ = 104	

*Rev. LMSC Report/Use Applic. Data

PERKIN-ELMER

OTD-6937

ORIGINAL PAGE IS
OF POOR QUALITY

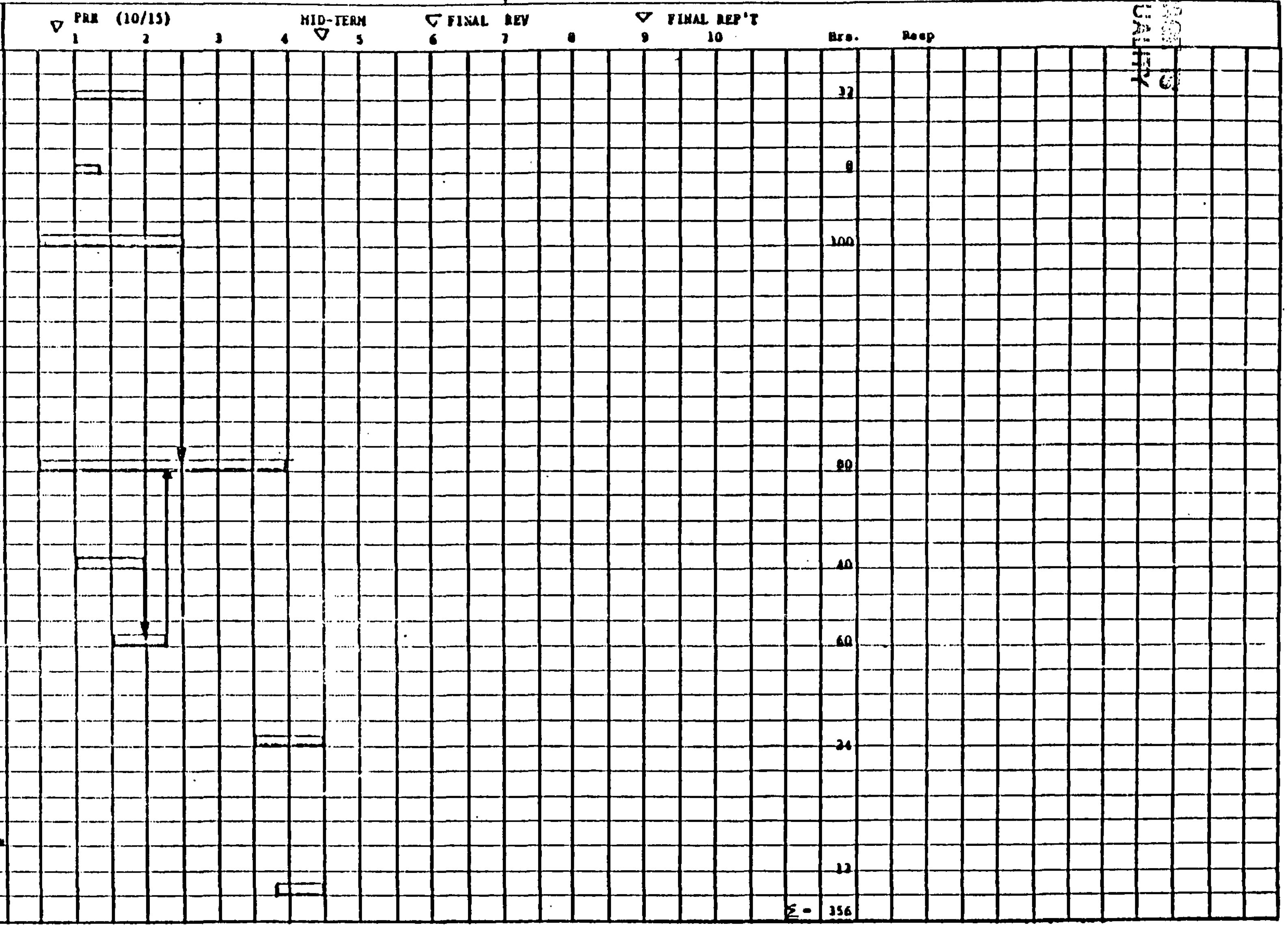
10/15/81 MK

C-2

LDR

M[illegible]TER PLANNING FORM
– MONTHLY –

10/5/81



	Hrs.	Resp
1. Technology Evaluations		
• Edge Effects on MTF	32	
2m vs. 4m		
hex vs petal		
• Deployment & Pkg'ing	8	
hex to petal		
hex rationale		
• Thermal Environments	100	
• Orbital heating/cooling		
• [illegible] temp profiles		
metal } config'ns		
glass } config'ns		
solid } config'ns		
sandwich } config'ns		
hybrid } config'ns		
• Mechanical Parameter		
Trades for:	80	
2m f/7.5, f/15		
4m f/7.5, f/3.75		
"thick" & "thin"		
Shallow shell check model	40	
circular		
hexagonal		
Temp Defn on } glass	60	
Freq } metals		
Stress } hybrids		
• Configuration/Performance		
Capabilities Summary:	24	
• Mat'ls & Weight vs		
~~Figure Stability~~		
• Other mat'l, config/n		
inherent characteristics		
• Parameter Definition for	12	
detailed models		
Σ =	356	

PERKIN-ELMER

OTD-6937

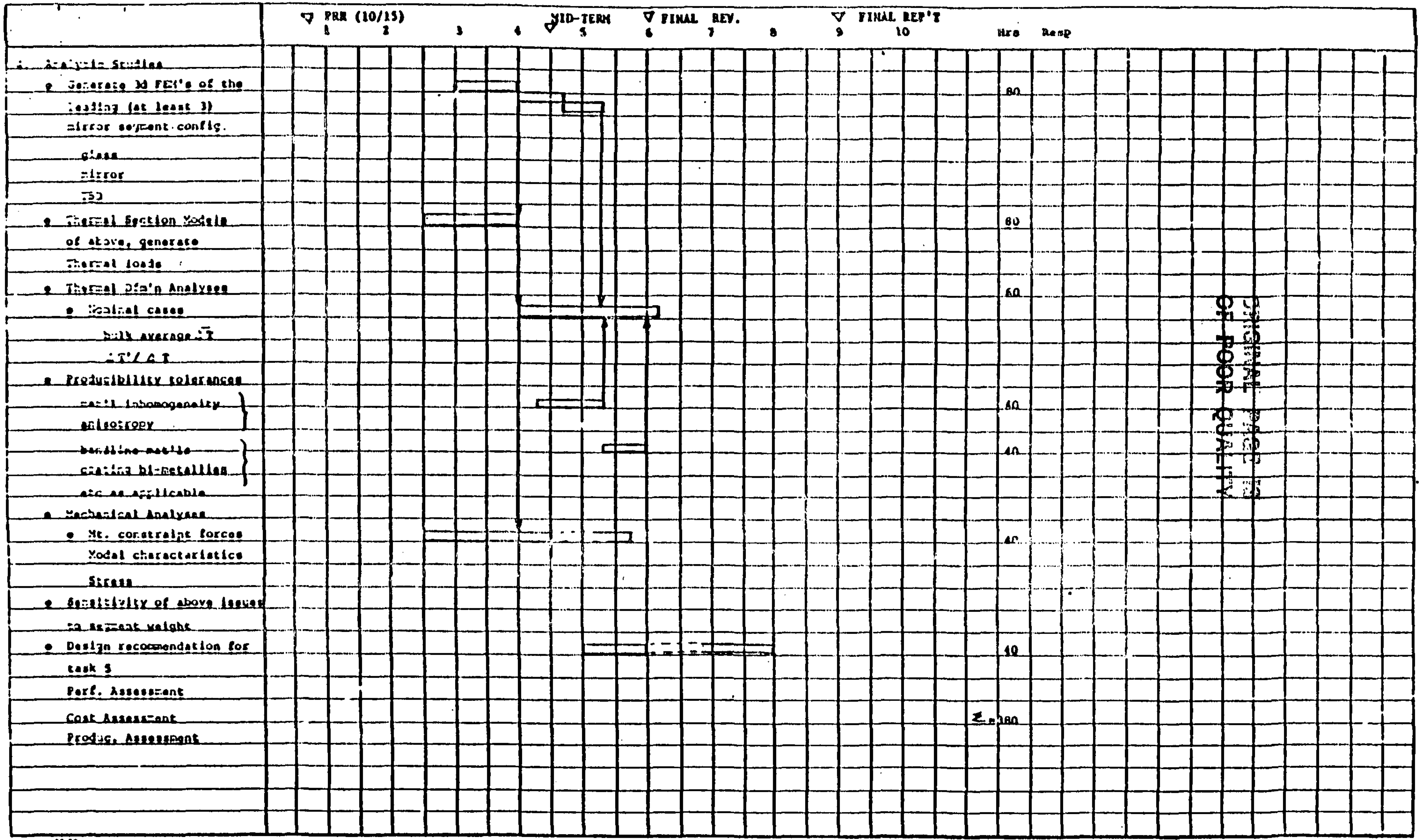
10/15/81 MK

LER

MASTER PLANNING FORM
MONTHLY –

3/4

10/5/81



	Hrs	Resp
1. Analysis Studies		
• Generate 3d FEM's of the	80	
leading (at least 3)		
mirror segment config.		
glass		
mirror		
TSD		
• Thermal Section Models	80	
of above, generate		
Thermal loads		
• Thermal Dfm'n Analyses	60	
• Nominal cases		
bulk average ΔT		
ΔT'/ΔT		
• Producibility tolerances		
matl inhomogeneity	40	
anisotropy		
~~bonding matls~~	40	
coating bi-metallics		
etc as applicable		
• Mechanical Analyses		
• Mt. constraint forces	40	
Modal characteristics		
Stress		
• Sensitivity of above issues		
to segment weight		
• Design recommendation for	40	
task 5		
Perf. Assessment		
Cost Assessment	Σ = 380	
Produc. Assessment		

ORIGINAL PAGE IS
OF POOR QUALITY

PERKIN-ELMER

OTD-6937

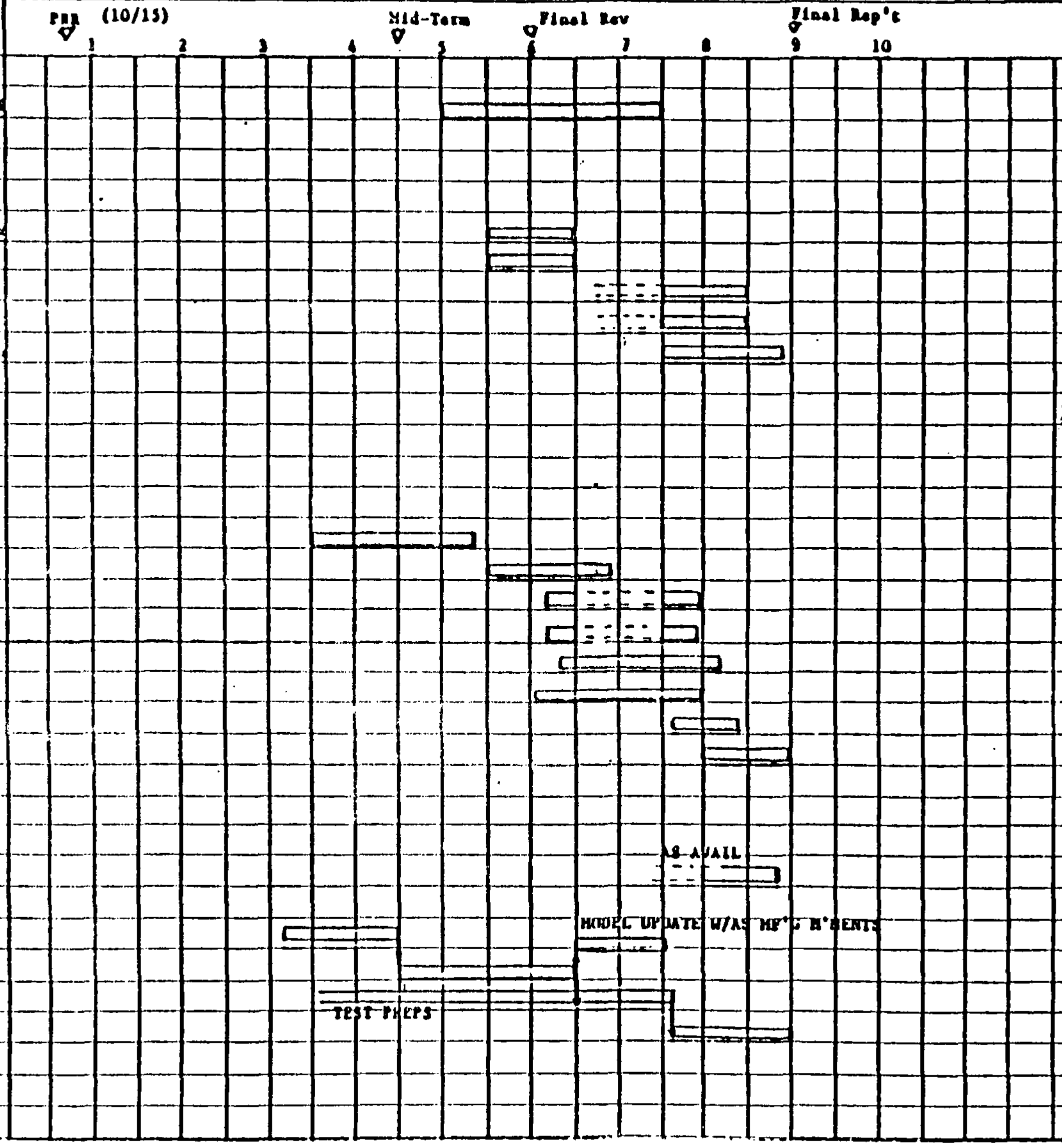
10/15/81 MK

LDR

MASTER PLANNING FORM
– MONTHLY –

4/4

10/5/81

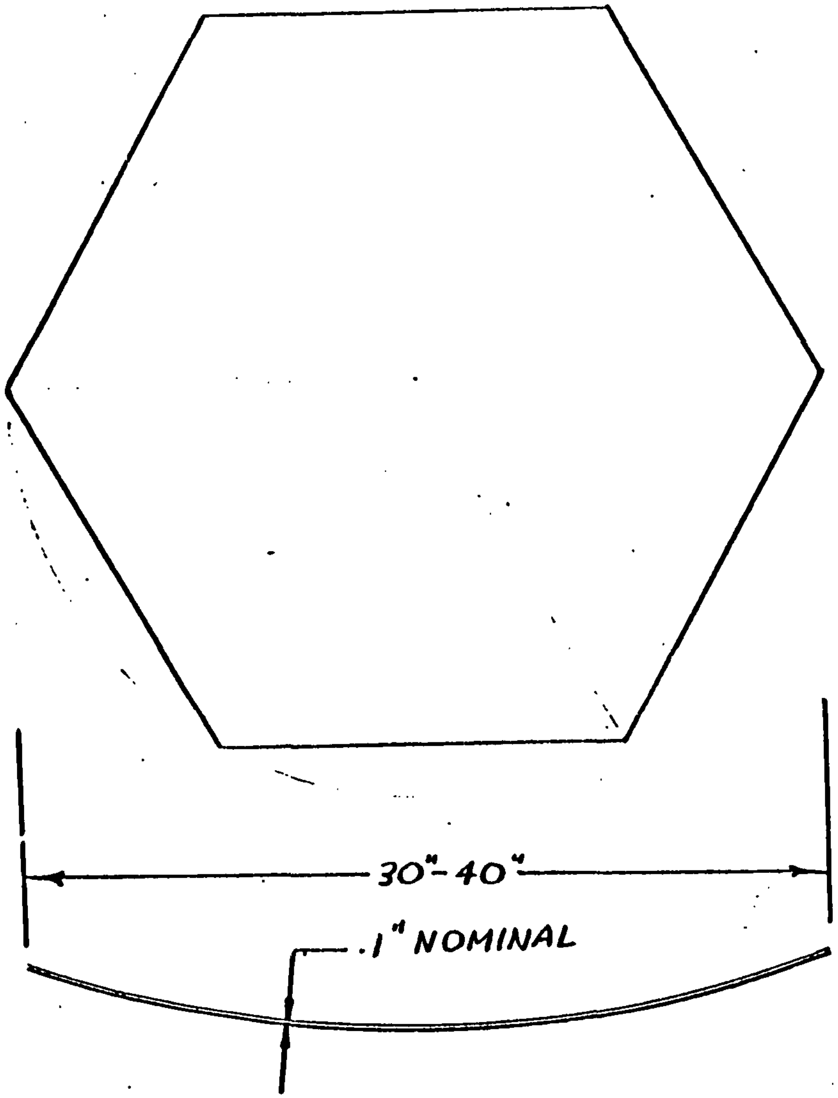


	HRS	RSP
5. DESIGN DEFINITION		
o Layout drawings, spec'ns, &	60	
& Crit. details of 2		
leading designs.		
o Producibility assessment		
dwg's & spec's to suppliers	20	
" " " DOD	10	
Facilities Devel. Req'ts.	40	
Tooling/Testing Req'ts	40	
o Overall critical evaluation	40	
of designs		
Identify risk areas	Σ = 210	
6. TEC. DEVELOPMENT PLAN		
Overall plan definition/obj.	40	
Update for specific config's.	20	
Subscale cost est.	"	
Fullscale cost est.	"	
Tooling & Facil. Est.	40	
Test Design	40	
In-House Review	"	
Comprehensive Plan Details	40	
	Σ = 160	
7. SUPPLEMENTARY EFFORTS		
IR&D Summaries		
Analysis Verif. Model		
Exp't Design		
H'ware Proc.		
Test		
Data Eval'n.		

10/15/81

MK

SUPPLEMENTAL EFFORT



TEST PIECE

OBJECTIVE

VERIFY ANALYTIC (FEM) OF HEX-AGONAL SHAPED SHALLOW SPHERICAL SHELL

- EDGE CURL ISSUE
- EMPHASIS ON CUSPS

10/15/81 MK

STUDY TASKS

TASK I

EVALUATION CRITERIA

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

10/15/81

EVALUATION CRITERIA

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 $\overset{\sim}{4}$ YEARS
- PRODUCIBLE AT ACCEPTABLE COST
  - ENSURE AN AFFORDABLE PROGRAM
  - ST MIRROR $460/LB AT RAW BLANK LEVEL
  - LDR GOAL $\leq$ $150/LB AT RAW BLANK LEVEL
- LOW THERMAL DISTORTION INDEX, $\rho \alpha C_P/K$
- 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

10/15/81 MK

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

10/15/81

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)

$$M_T \quad \frac{h^2 t_f E_f \overline{\Delta T}(\alpha_c - \alpha_F)}{2R(1-\nu)} \quad \text{in lb/in}$$

  - INHERENT DESIGN PROPERTY
- MINIMIZATION OF MATERIAL REMOVAL
  - FIGURE TIME
  - INTERNAL STRAIN UNBALANCE

CONTINUED ON PAGE 6

10/15/81 MK

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 ORTHAGONALITY
- MODELLABILITY
  - ACCURATE MODELLING

10/15/81

TASK II

ASSESS TECHNOLOGY

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
  λ/40 RMS VISIBLE
- SPACE TELESCOPE 60" Ø
  4" THICK SOLID DEMONSTRATE FIGURING (λ/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

10/15/81 MK

TECHNOLOGY MIRRORS AT PERKIN-ELMER

(CONTINUED)

- FOAM CORES

  AS EARLY AS 1960 AND STILL A CONSIDERATION.

ELSEWHERE:

ITEK: FUSED SILICA S/L MACHINNED 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)

TASK III

IDENTIFYING & EVALUATION

OF

PRIME TECHNOLOGIES

SOME CONFIG'N OPTIONS	ULE	FUSED SILICA	TGC	FUSED QUARTZ	ZERO-DUR	PYREX	COIL-ZAK (ALUMINUM)	BERYLIUM	PLASTICS/RESINS
THIN SOLIDS	X	X	X	X		X		X	
EXTERNALLY BRACED THIN SOLIDS	X	X	X	X		X	X	X	X
GLASS SANDWICHES MONOLITHIC	X	X		X					
GLASS/CERAMIC SANDWICHES			X		X				
REPLICATED OR PRECISION SAGGED, FORMED			X			X	X		X
ISOGRID TYPES I.E., MACHINED SOLIDS				X	X	X		X	
METALLIC SANDWICHES							X	X	

10/15/81 MK

SOME MATERIAL POSSIBILITIES

MATERIAL	APPLICATION	THERM COMPAT. @ - 100^0F	INHERENT LIGHTISITY	PRODUCIBILITY ASSESSMENT
CORNING ULE	MONOLITH S/W	POOR	FAIR	COSTLY
CORNING FUSED SILICA	MONOLITH S/W	EXCELLENT	FAIR +	LESS COSTLY
CORNING TGC	FACESHEET	?	FAIR +	S/B CHEAP
CORNING VYCOR	TUBE CORE	?	?	
HERAEUS FUSED QUARTZ	MONOLITH S/W	EXCELLENT	FAIR +	COSTLY
PYREX	"CHEAP" MIRRORS	POOR	POOR	S/B CHEAP
BATTELLE $S1O_2$-$T1O_2$ SOL-GEL	FACESHEETS	?	?	COSTLY
SCHOTT ZERODUR	FACESHEET	POOR-FAIR	POOR	COSTLY
ALUMINUM (5K)	FACESHEETS	FAIR-AWFUL	GOOD	CHEAP
COIL-ZAC ALUMINUM	FACESHEETS	FAIR-AWFUL	GOOD	MICRO-FINISH ?
BERYLLIUM	THIN, OPEN SOLIDS	FAIR-AWFUL	GOOD +	VOLUME ISSUE
"LOST WAX" BERYLLIUM	MONOLITHIC "RED"	FAIR-AWFUL	GOOD ++	VOLUME, EXP.
GRAPHITE EPOXIES	SUPPORT TRUSSES	GOOD	N/A	AVAIL.
LMSC GRAPHITE-MAG	SUPPORT TRUSSES	GOOD	N/A	COMING ALONG!
GLASSY CARBON	THIN SOLIDS	?	?	SMALL SIZES

CONTINUED

10/15/81

SOME MATERIAL POSSIBILITIES

(CONTINUED)

MATERIAL	APPLICATION	THERM COMPAT. @ - 100°F	INHERENT LIGHTISITY	PRODUCIBILITY ASSESSMENT
CORNING ULE TUBES	CORES	POOR	GOOD	FEASIBLE
CORNING F/S TUBES	CORES	GOOD	GOOD	FEASIBLE
HERAEUS QUARTZ TUBES	CORES	GOOD	GOOD	AVAIL.
ULE FRITS	JOINTS	N/A	N/A	AVAIL.
FUSED SILICA FRITS	JOINTS	N/A	N/A	AVAIL.
TGC FRITS	LOTSA LUCK!!	N/A	N/A	INVEN. REQUIRED
FOAMED CORE MATERIALS	CORES	GOOD	FAIR	YESSESS & NO'S
CORNING CER-COR	CORES	?	FAIR	FEASIBLE

10/15/81 MK

OTHER TASKS

IV

V

VI

NEAR-TERM ACTIVITIES

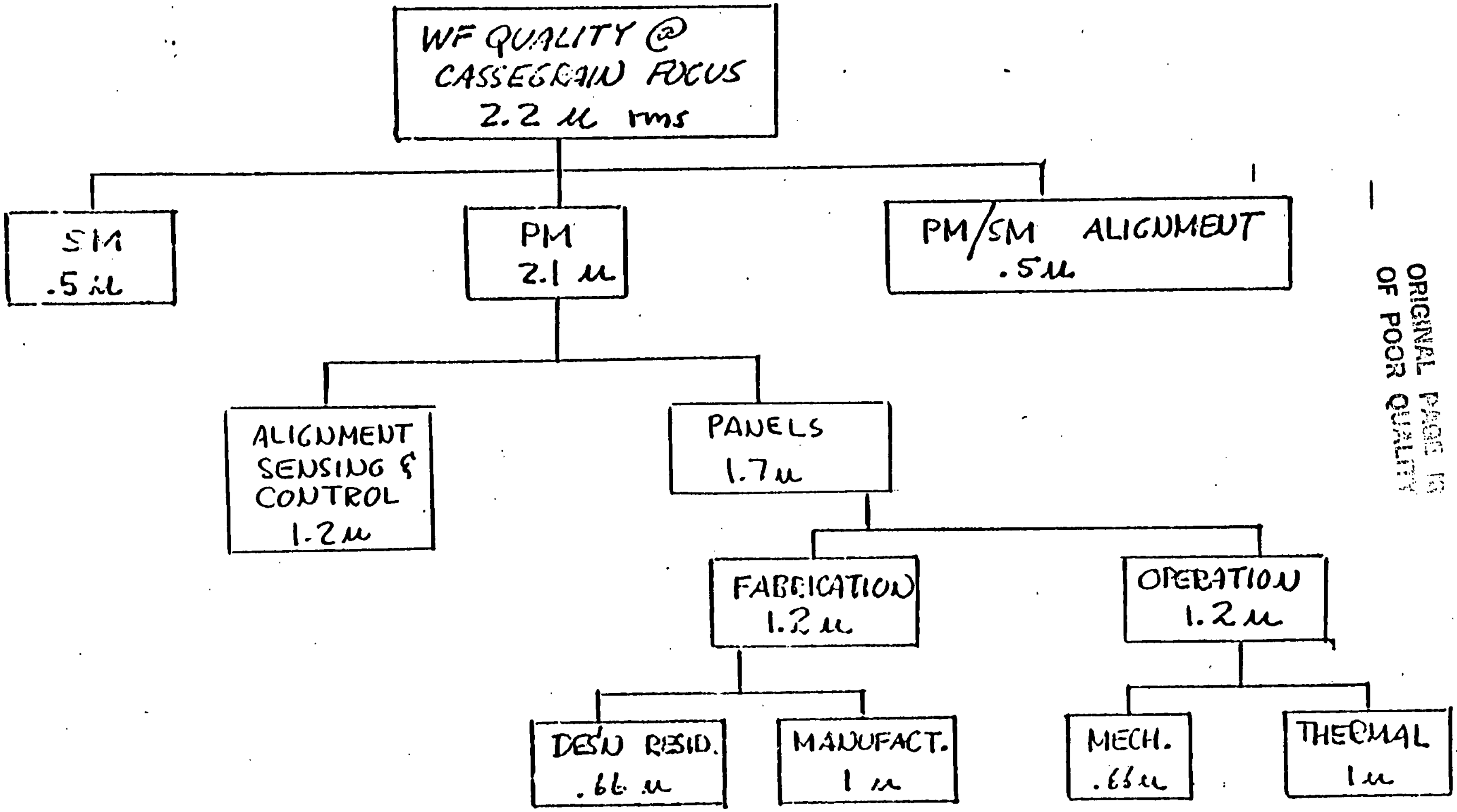
- PRIORITIZE EVALUATION CRITERIA
  - WEIGHTING FACTORS
- IN-DEPTH TOP LEVEL REQ'TS REVIEW
  - ENSURE 0A CONCLUSIONS APPROPRIATE FOR SYSTEM & SEGMENT REQ'TS
- SEGMENT-TO-SEGMENT TEMPERATURE VARIATIONS
  - $\Delta\bar{T}$, $\Delta T'/H$, TRANSIENTS
  - KEY MAT'L SORTING ISSUE
  - SEE IF ANY CANDIDATES DROP OUT!

10/15/81

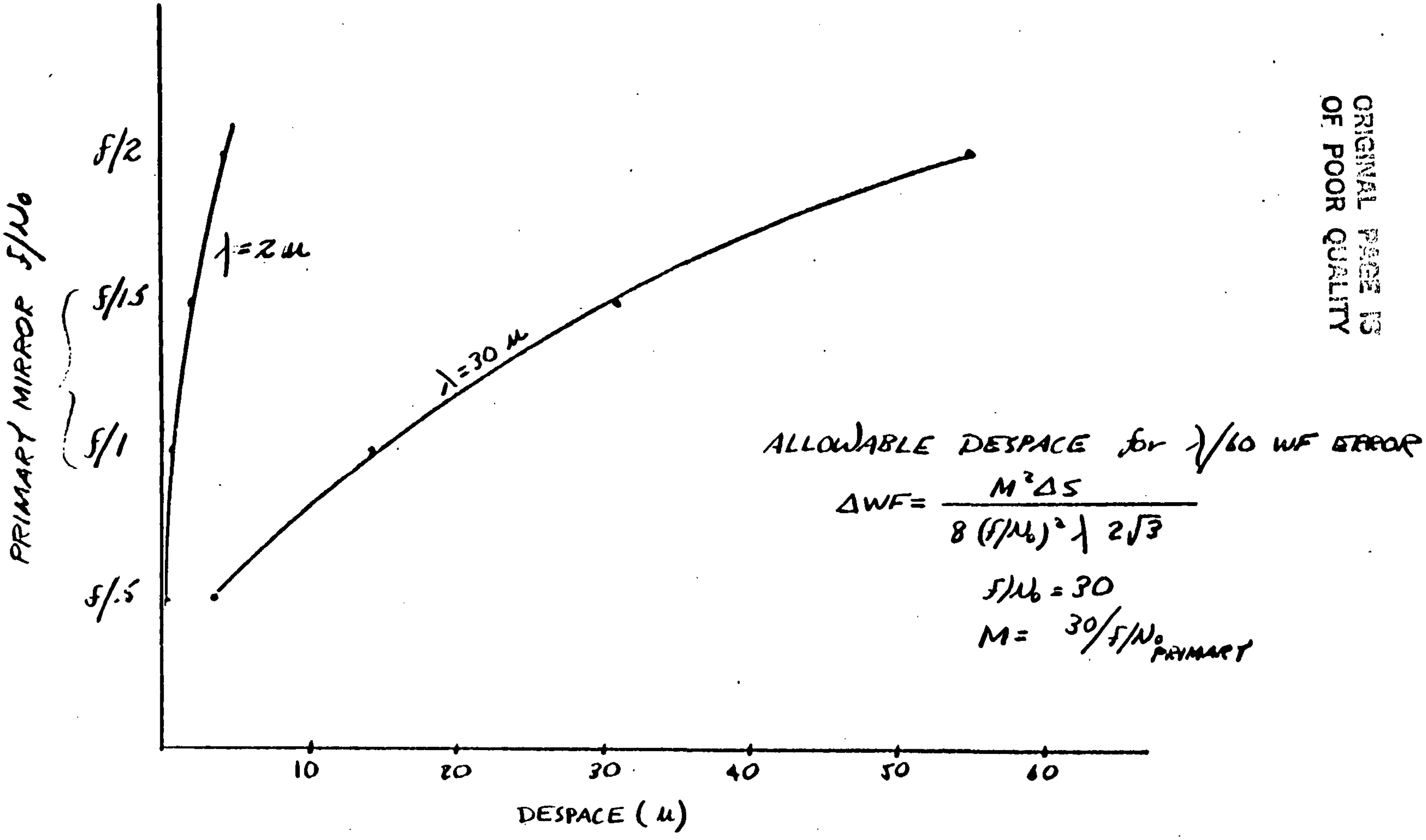
STATIC ERROR BUDGET

D/L PERFORMANCE ≡ $\lambda/13.7$ rms

FOR $\lambda = 30\,\mu$, $2.2\,\mu$ rms WF REQ'D



10/15/81 MK



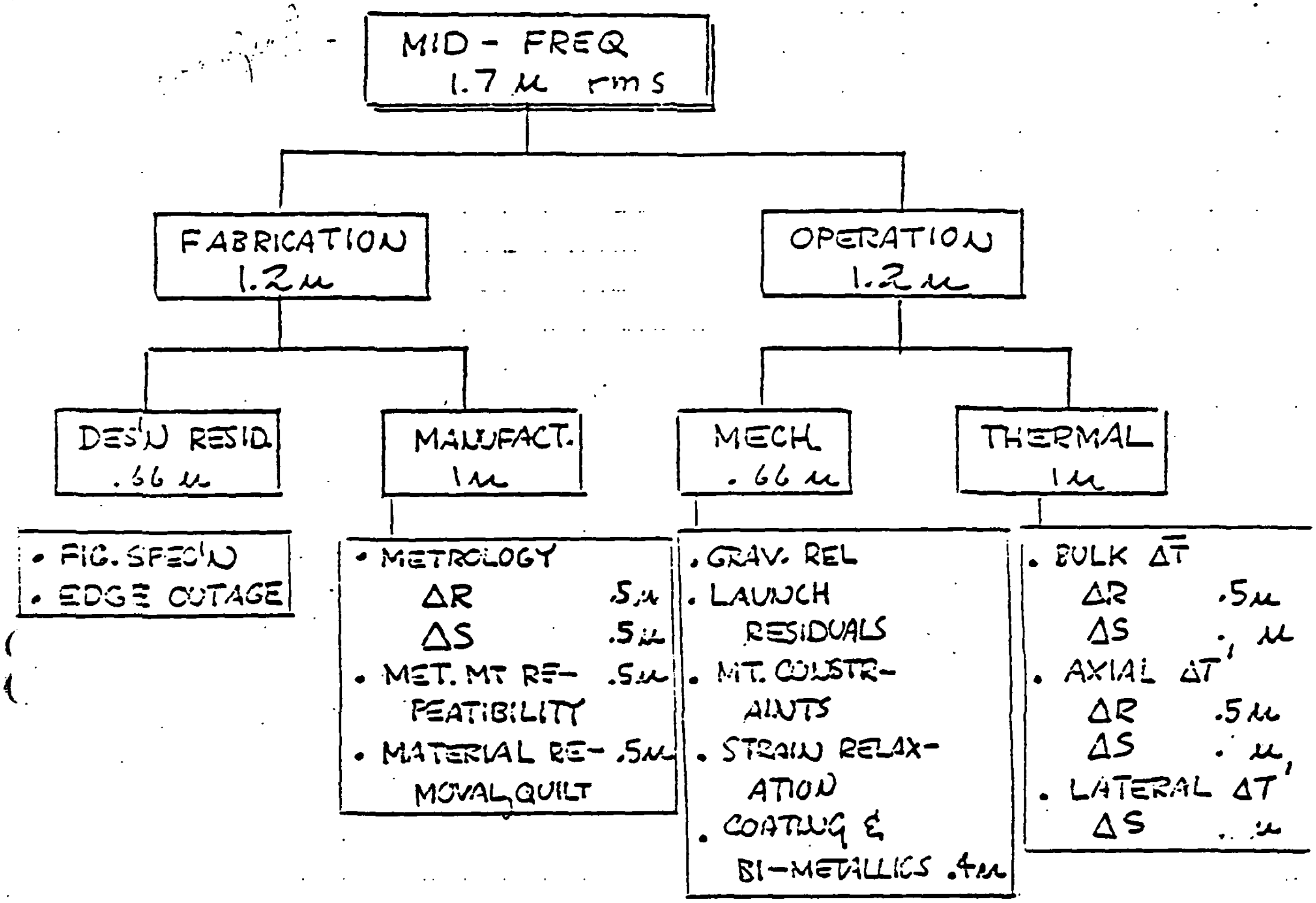
ALLOWABLE DESPACE for λ/60 WF ERROR

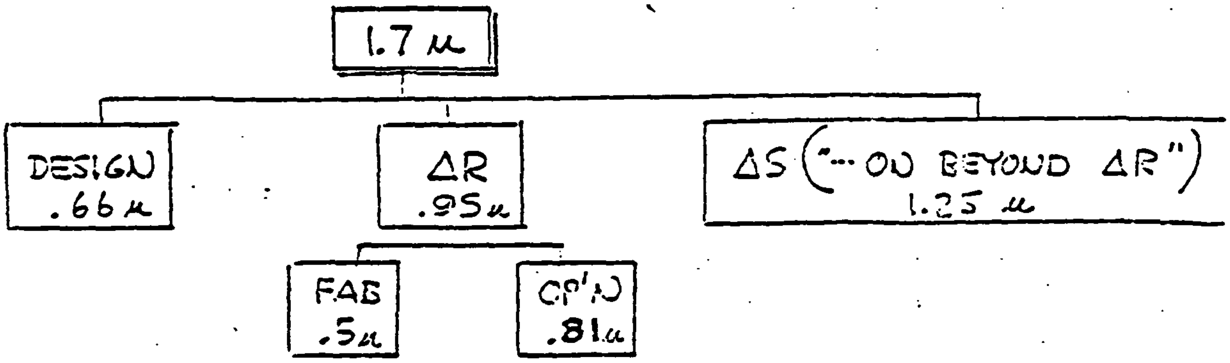
$$\Delta WF = \frac{M^2 \Delta S}{8 (f/N_0)^2 \lambda \; 2\sqrt{3}}$$

$f/N_0 = 30$

$M = 30 / f/N_{0_{PRIMARY}}$

SEGMENT ERROR BUDGET





10/15/81 MK

REPRESENTATIVE

SEGMENT DESIGN PARAMETERS

SYSTEM APERTURE

	10M				15M				30M			
PRIMARY F/NO	F/1		F/.5		F/1		F/.5		F/1		F/.5	
R (M)	20		10		30		15		60		30	
SEG. DIA (M)	2.	4.	2.	4.	2.	4.	2.	4.	2.	4.	2.	4.
SEG. F/NO	5	2.5	2.5	1.25	7.5	3.8	3.8	1.9	15	7.5	7.5	3.8
Δ R TOTAL (MM)	±1.2	.3	.3	.08	± 2.6	.7	.7	.16	±10.4	2.6	2.6	.66
Δ R/R %	.006	.0014	.0029	.0008	.0086	.002	.0043	.0011	.017	.004	.009	.0022
ΔR_{MFG} (MM)	±.61	.15	.15	.041	± 1.4	.36	.36	.08	±5.5	1.4	1.4	.36
ΔS_{MFG}	~ .68λ RMS EQUIVALENT VISIBLE FIGURE ~											
AREAL DENSITY	LB/IN²		(141 KG/M²)		.089 LB/IN²		(63 KG/M²)		.022	LB/IN²	(16 KG/M²)	
MAX THICKNESS		19 "				15 "				6 "		
CTE REQ'TS	ALL VALUES X $10^{-6}/°F$											
$\Delta \bar{T}$ = 20°F 1°F/in	2	.5	1	.26	3.2	.8	1.6	.4	6.4	1.6	3.2	.8
$\Delta T^{1}/H$ = 1°F/M	.05	.013	.05	.013	SAME				SAME			
NO. REQ'D	19	7			42	16			217	61		

NOTES: ΔR_{TOTAL} EQUIVALENT TO .95μ RMS WF ERROR
$\Delta \bar{T}$ " " .7μ " " "
$\Delta T^{1}/H$ " " .7μ " " "

TYPO 5/8 1°F/inch

10/15/81 MK

TOLERANCING SEGMENTED MIRRORS

- SEGMENT-TO-SEGMENT RADIUS OF CURVATURE MATCHING IS REQUIRED
- $\Delta WF_{rms} = \frac{1}{3}\left(\frac{r}{R}\right)^2 \Delta R$
- NEW REQUIREMENT WITH RESPECT TO MONOLITHIC MIRRORS

$$\Delta R = \frac{R^2 \alpha \Delta T}{h}$$

$$\therefore \Delta WF_{rms} = \frac{1}{3} \frac{\cancel{r^2}}{\cancel{R^2}} \frac{\cancel{R^2} \alpha \Delta T}{h} \times \left(\frac{d}{2r}\right)^2$$

$$\Delta WF = \frac{1}{12} \frac{d^2 \alpha \Delta T}{h}$$

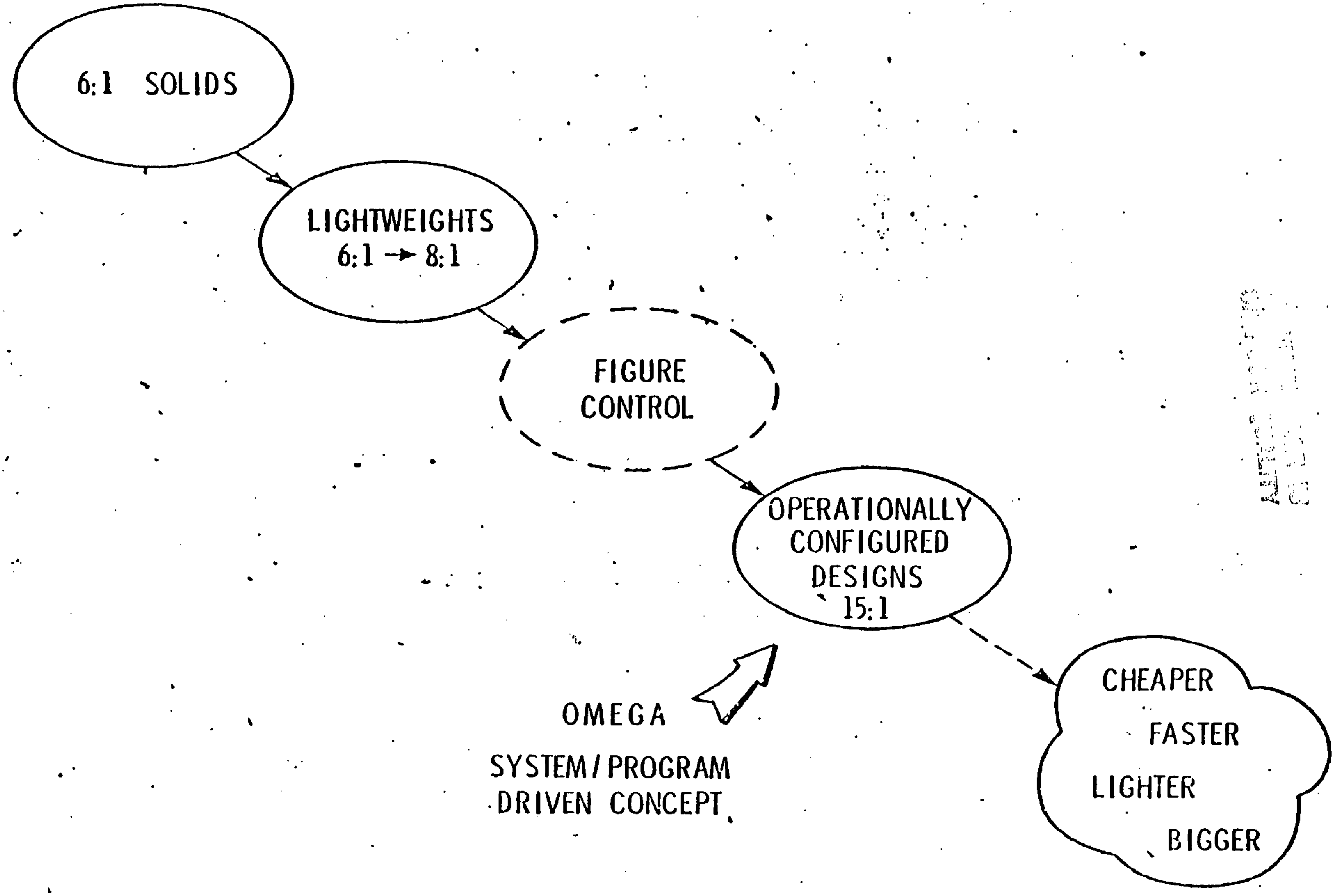
10/15/81 MK

BEFORE I CONCLUDE......

OPTIMUM MIRROR STRUCTURE DESIGN

- DISREGARD MINIMUM FACEPLATE THICKNESS, CORE DENSITY, AND CORE CELL SIZE CONSTRAINTS.
- OPTIMIZE STRUCTURES AND IDENTIFY BIG PAYOFF AREAS.
- 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

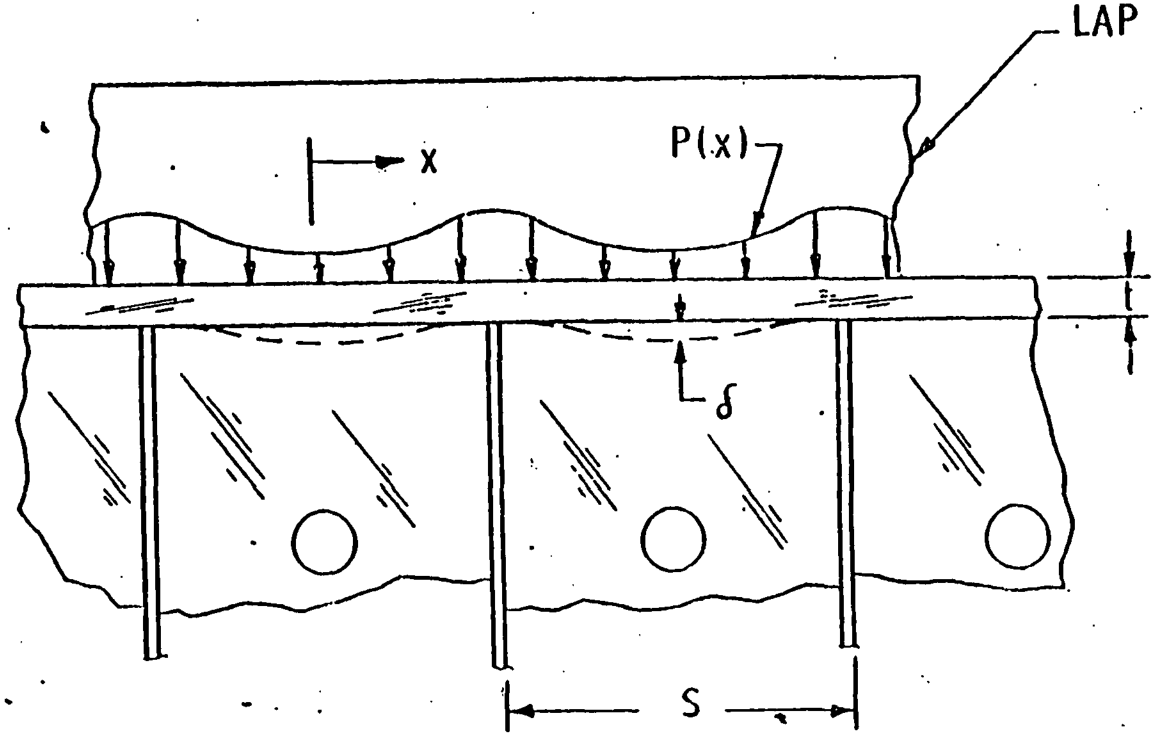
OPERATIONALLY
CONFIGURED
DESIGNS
15:1

CHEAPER
FASTER
LIGHTER
BIGGER

OMEGA
SYSTEM/PROGRAM
DRIVEN CONCEPT

10/15/81 MK

CORE GEOMETRY - FACEPLATE RELATIONSHIP



$$\left.\begin{aligned} P(x) &= f(\delta) \\ \delta &= f\left(\frac{S^4}{t^3}\right) \end{aligned}\right\} \quad \frac{S^4}{t^3} = 607 \rightarrow 640$$

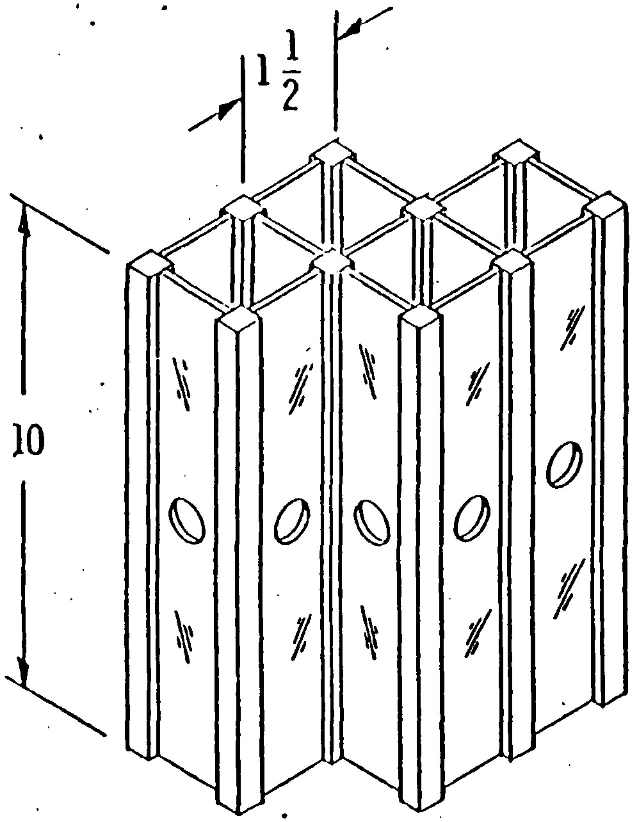
TODAY'S EXPERIENCE

BY THESE STANDARDS, S = 1.5 INCHES
IF t = 0.2" INCHES.

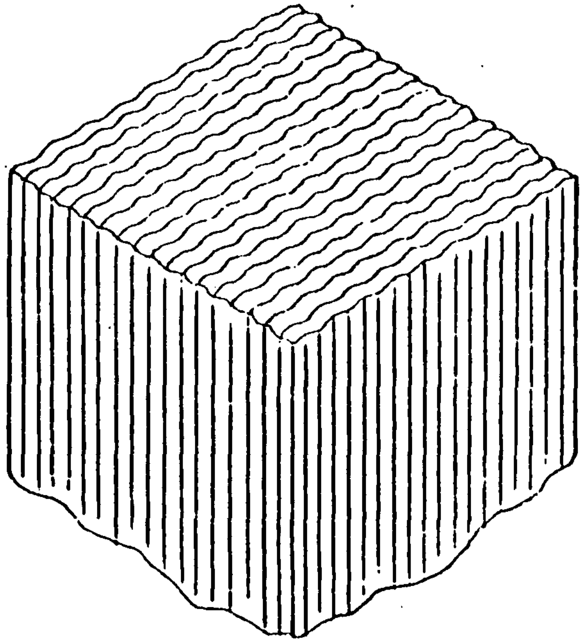
10/15/81 MK

CONCEPT SAMPLES

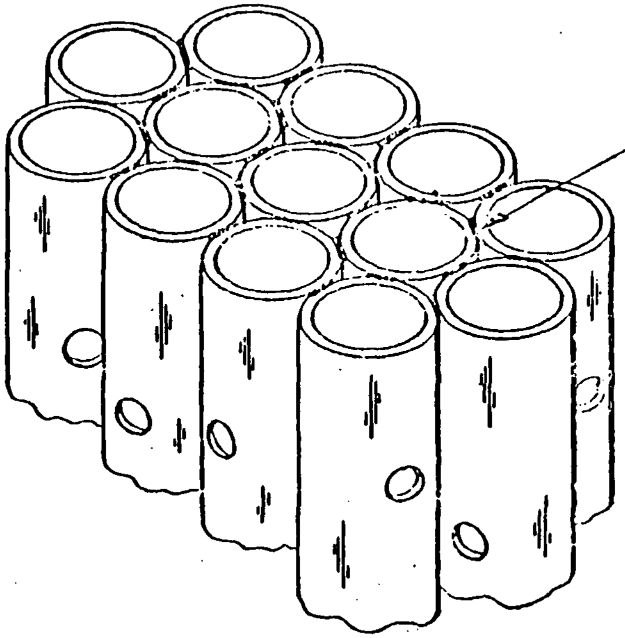
SMALLER CELL SIZE CONCEPTS



ULE



SLIP CAST SILICA
(80% OPEN)

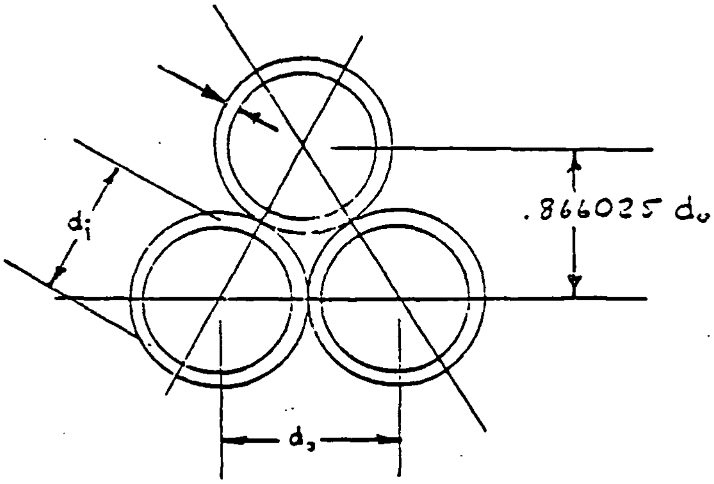


VYCOR (FUSED SILICA)

10/15/81 MK

TUBE CORE DESIGN

OF POOR QUALITY



NET AREA $= .433013\ d_o^2$

SOLID AREA $= \frac{1}{2}\frac{\pi}{4}\left(d_o^2 - d_i^2\right)$

$$d_i = d_o - 2t \quad , \quad d_i^2 = d_o^2 - 4d_o t + 4t^2$$

$$d_o^2 - d_i^2 = \cancel{d_o}^2 - \cancel{d_o}^2 + 4d_o t - 4t^2$$

$$\cong 4d_o t \quad \text{when} \quad t \ll d_o$$

$\therefore$ SOLID AREA $= \frac{1}{2}\frac{\pi}{4}\left(4d_o t\right)$

$$\text{SOLID/NET} = \frac{\pi d_o t}{2 \times .433013\ d_o^2} = 3.63\frac{t}{d_o}$$

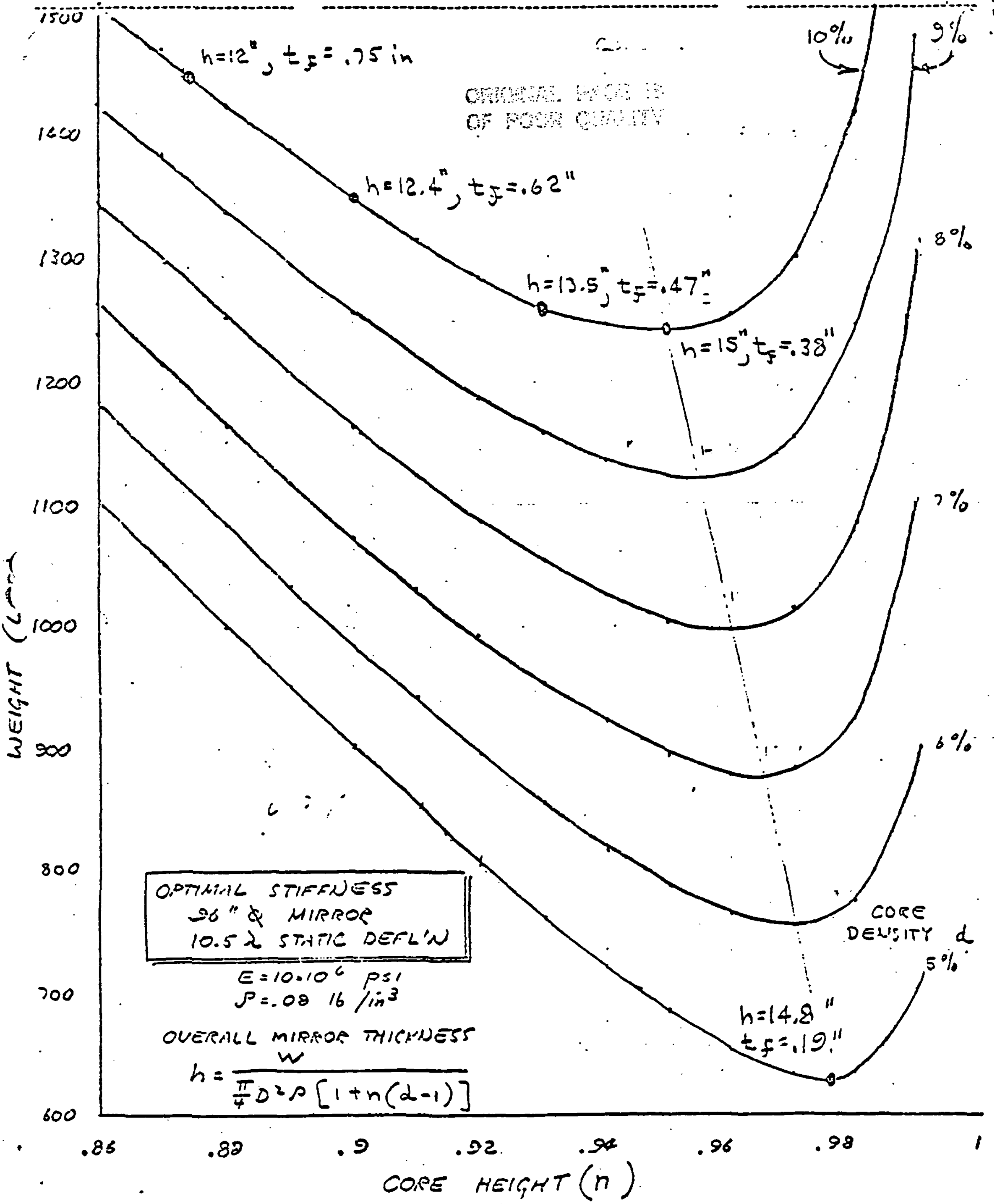
EXAMPLE

.18 FACESHEETS ⟶ 1" CELL SPAN, i.e. $d_o \cong 1"$

t	.01"	.015	.02	.025	.03	.035
% ρ_{eff}	3.6	5.4	7.3	9.1	10.9	12.7

10/15/81 MK

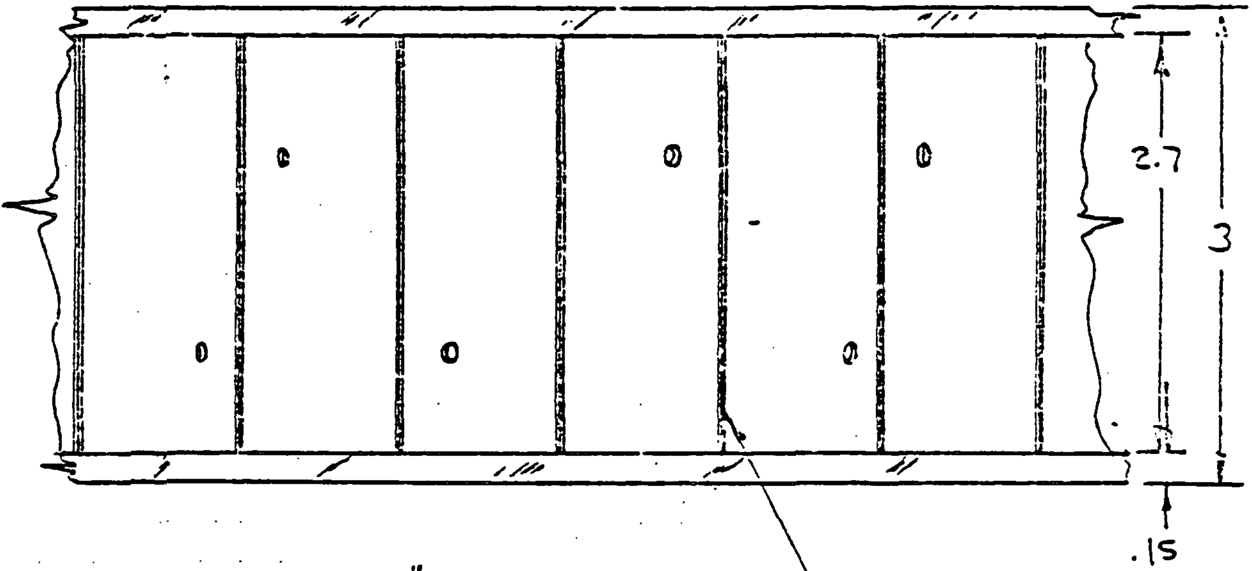
BY ________ DATE ________ SUBJECT ____________________ SHEET NO. ________
CHKD. BY ________ DATE ________ ____________________ JOB NO. ________



80" ⌀ MIRROR DESIGN EXAMPLE

FUSED SILICA
FRIT JOINED

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



1"x.015 TUBING
(5.4% SOLID DENSITY)

WEIGHT $W = \frac{\pi}{4} \times 80^2 \times \rho (2 t_f + n h_c) = 176$ lbs

STRESS @12g ULT $\sigma = \frac{Wgt}{t_e^3} = 865$ psi

DEFL'N @1g $\Delta = .036 \frac{Wr^2}{E t_e^3} 12(1-\nu^2) = .00171"$ $(1.42\lambda$ @ $30\mu)$

FREQ $f = \frac{1}{2\pi}\sqrt{\frac{25EIg}{Wr^2}} = 72$ cps

10/15/81 MK

CHANGING DIAMETER TO 160":

W = 704 LBS

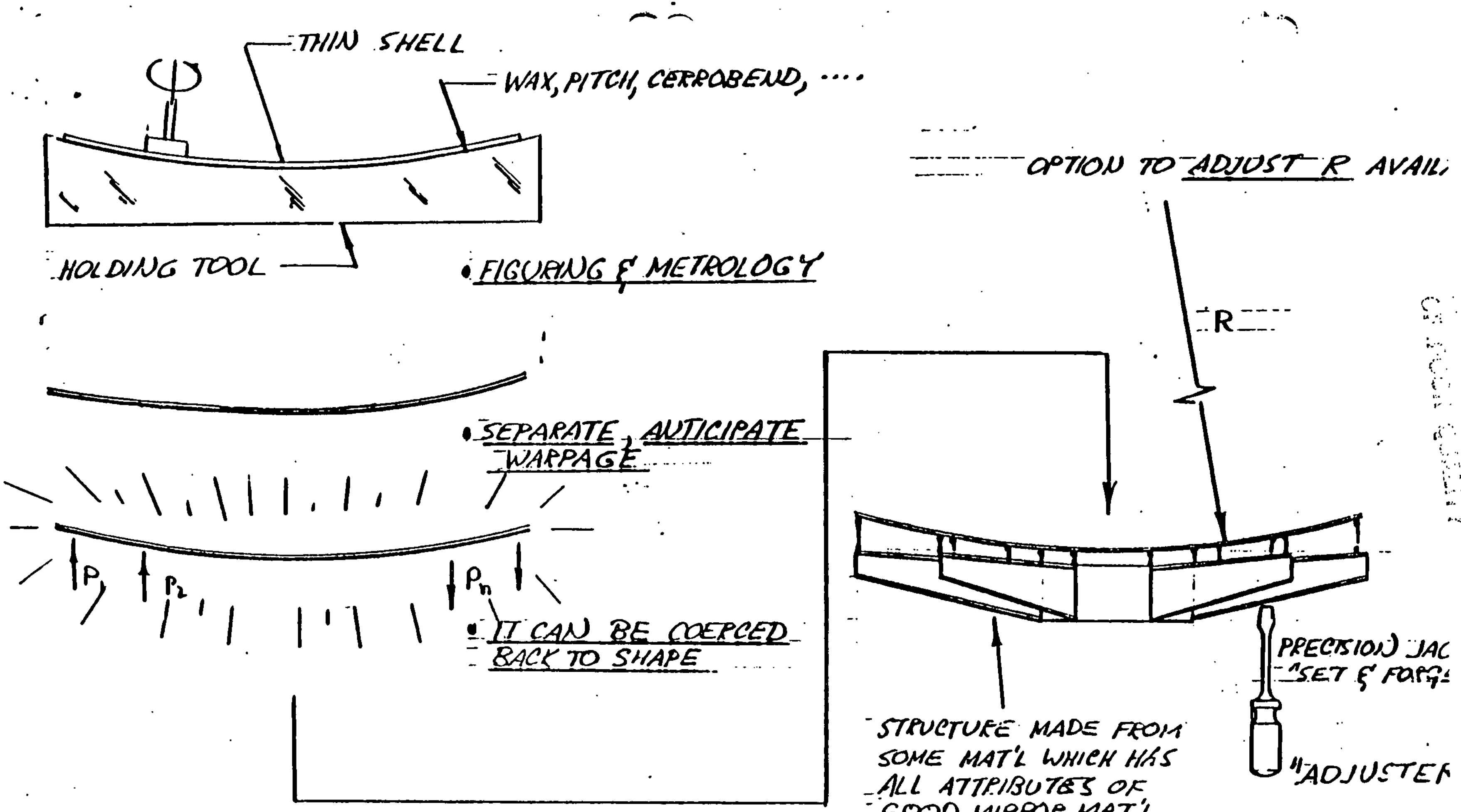
STRESS σ= 3463 PSI

DEFL'N Δ= .0272" (22λ @ 30 μ)

FREQ F_1 = 18 CPS

10/15/81 MK

HYBRID MIRROR



- FIGURING & METROLOGY
- SEPARATE, ANTICIPATE WARPAGE
- IT CAN BE COERCED BACK TO SHAPE

STRUCTURE MADE FROM SOME MAT'L WHICH HAS ALL ATTRIBUTES OF GOOD MIRROR MAT'L EXCEPT ITS NOT POLISHABLE

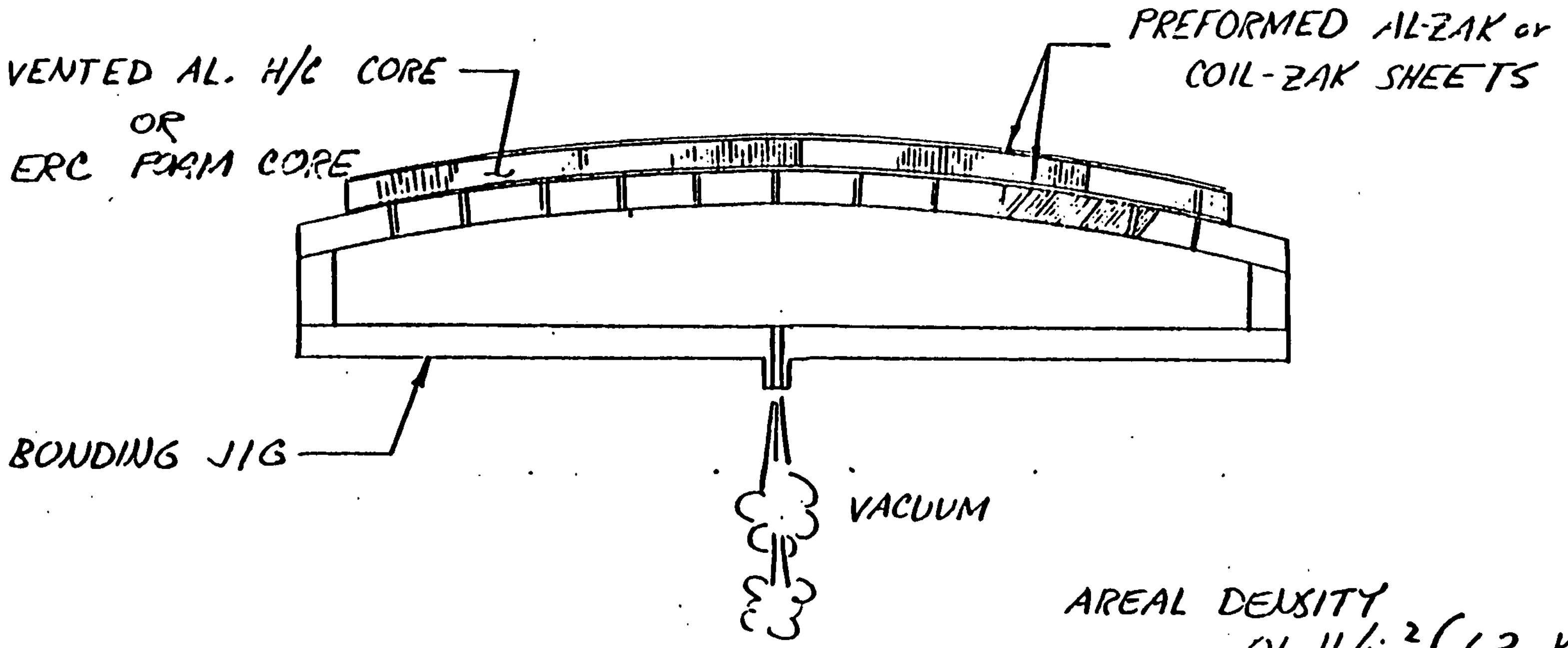
- CTE MATCHES THIN SHELL
- LONG TERM STABILITY
- LIGHT, EFFECIENT FORMS
- LOW COST (REL. TO GLASS)

DUAL-α GRAPHITE EPOXY TRUSS
GRAPHITE MAGNESIUM (LMSC)

OR

- REPLICATE:
  - PLASTICS, RESINS
  - ELECTOFORM
    - ALUMINUM (TRW)
- FORMED ALUMINUM
  - COIL-ZAK

10/15/81 MK

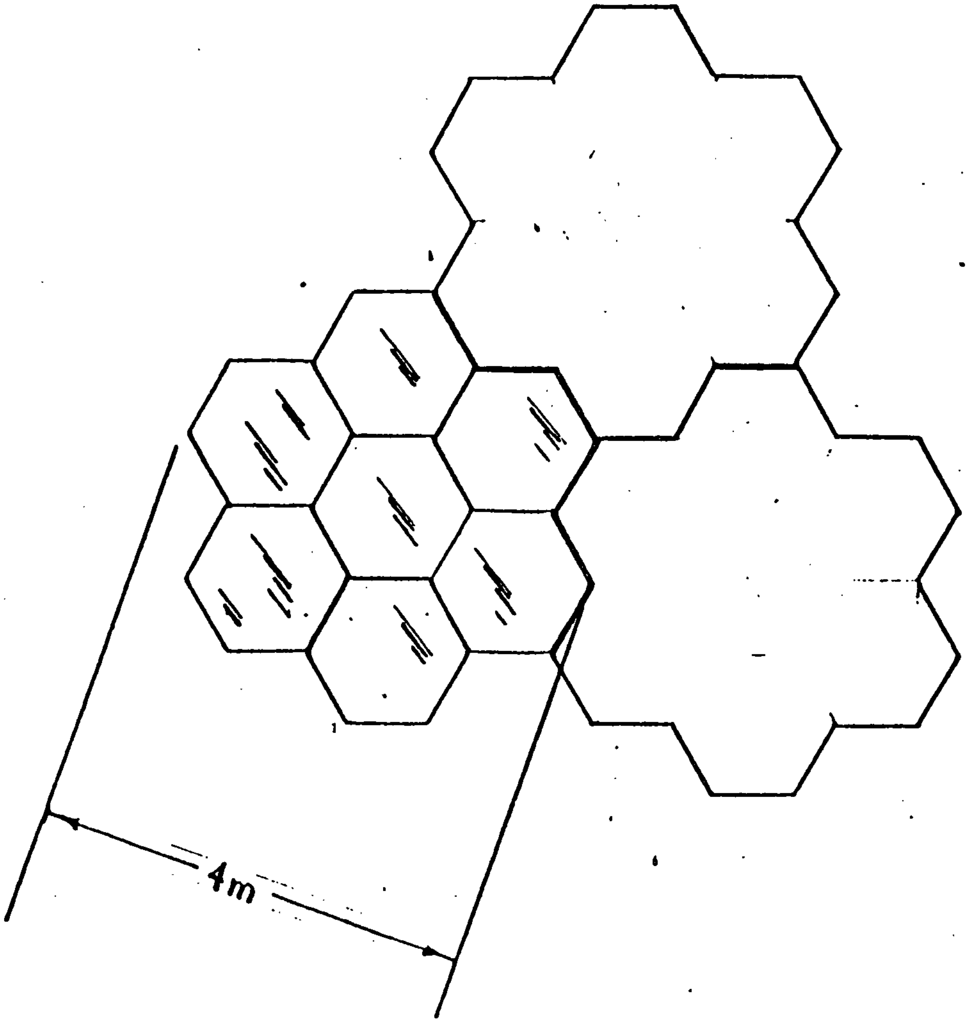


AREAL DENSITY
$.01\ \mathrm{lb/in^2}\ (6.3\ \mathrm{Kg/m^2})$

ISSUES:
- ADHESIVES
  - THICKNESS UNIFORMITY $\Delta S = f(\alpha \Delta t)\Delta \bar{T}$
  - BENDING MOMENT
- SPRING BACK
- OUTGASSING/COATING CH. COMPATIBILITY

ALUM. SEGMENTS for WELL CONTROLLED THERMAL ENV'T

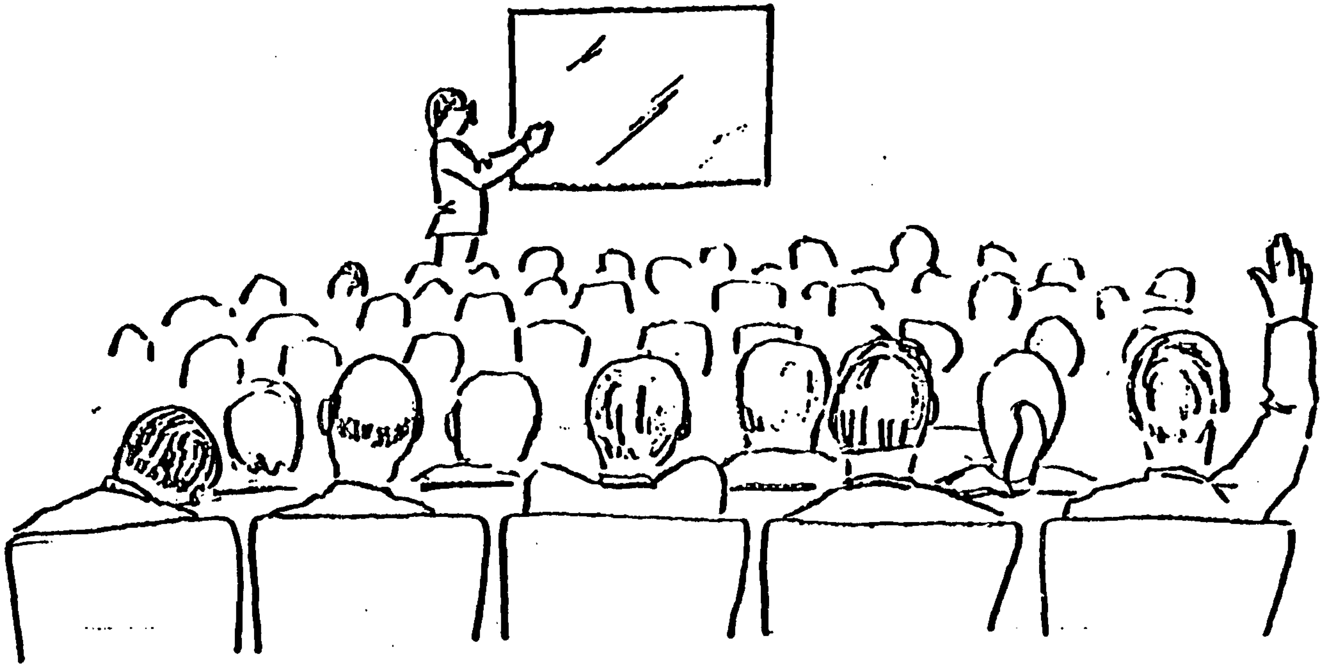
i.e. $\Delta \bar{T} \leq 5°F$, $\Delta T'/h \leq .004°F/in$ or $\Delta T' \leq .01°F$



PRE-ASSEMBLED SMALL SEGMENT MODULES

FACILITATES SMALL SEGMENT ERECTABILITY

ARE THERE ANY QUESTIONS ?



LDR
SEGMENTED MIRROR TECHNOLOGY ASSESSMENT STUDY

INTERIM REVIEW

APPENDIX B

LDR INTERIM REVIEW

L D 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	MIKE KRIM	9^{30}-9^{50}
• EVALUATION CRITERIA	"	9^{50}-11^{15}
• CURRENT TECHNOLOGY ASSESSMENT	"	11^{15}-11^{45}
• IDENTIFY & EVALUATE PRIME TECHNOLOGIES	"	11^{45}-12^{15}
~ LUNCH ~		
• ANALYTIC STUDIES		
STRUCTURES	GREG RUTHVEN	1^{30}- 2^{15}
THERMAL	MIKE KRIM	2^{15}- 2^{30}
• PANEL EXPERIMENT	"	2^{30}-2^{50}

PROGRAM OVERVIEW

PROGRAM OBJECTIVES & TASK STRUCTURE

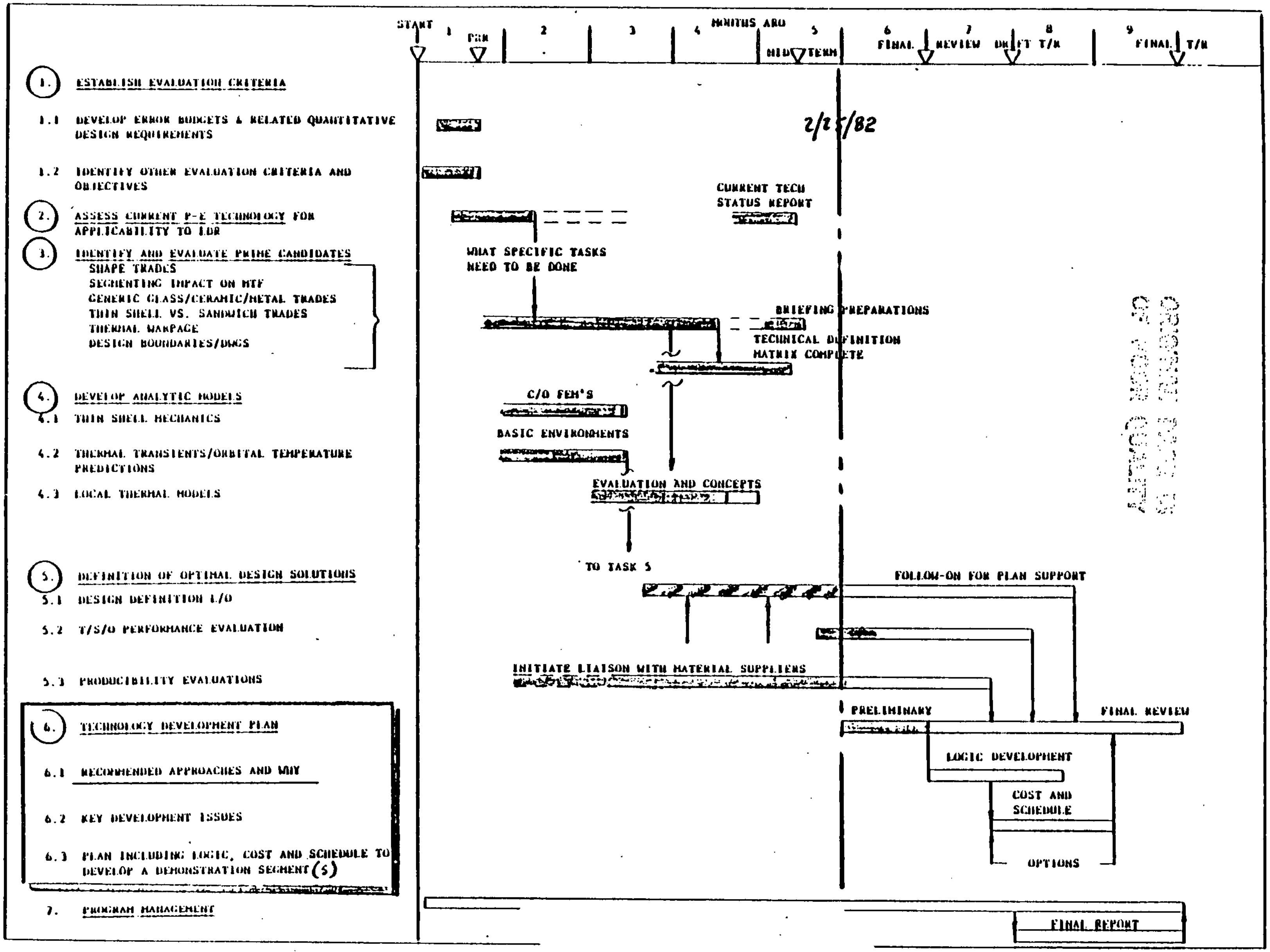
PANEL REQ'TS SYNOPSIS

THE ΔR ISSUE AND OTHER····

KEY TECHNICAL ISSUES

(5)

LDR



OBJECTIVE: IDENTIFY 2 MOST PROMISING CANDIDATES
& PREPARE DEVELOPMENT PLANS.

6

TOP LEVEL LDR REQUIREMENTS

(FROM SOW & ATTACHMENTS)

OVERALL DIA...............	$10 \leq D \leq 30$ M
FIGURE TYPE...............	PARABOLA OR HYPERBOLA/NOT SIMPLY SPHERICAL
FIGURE QUALITY...........	$\left.\text{D/L @ } 30\,\mu \rightarrow \frac{\lambda}{13.7} \text{ RMS OR } 2.2\,\mu\right]_{\text{SYSTEM}} \longrightarrow 2\,\mu_{\text{RMS}}$ MIRROR
SPEED.....................	F/.5 TO F/1
WEIGHT....................	25000 LBS (11360KG)
OPERATING TEMP...........	150 - 200°K (-100 TO -190°F)
OPERATING W/L............	$2\,\mu$ TO $1000\,\mu$
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

10/15/81 MK

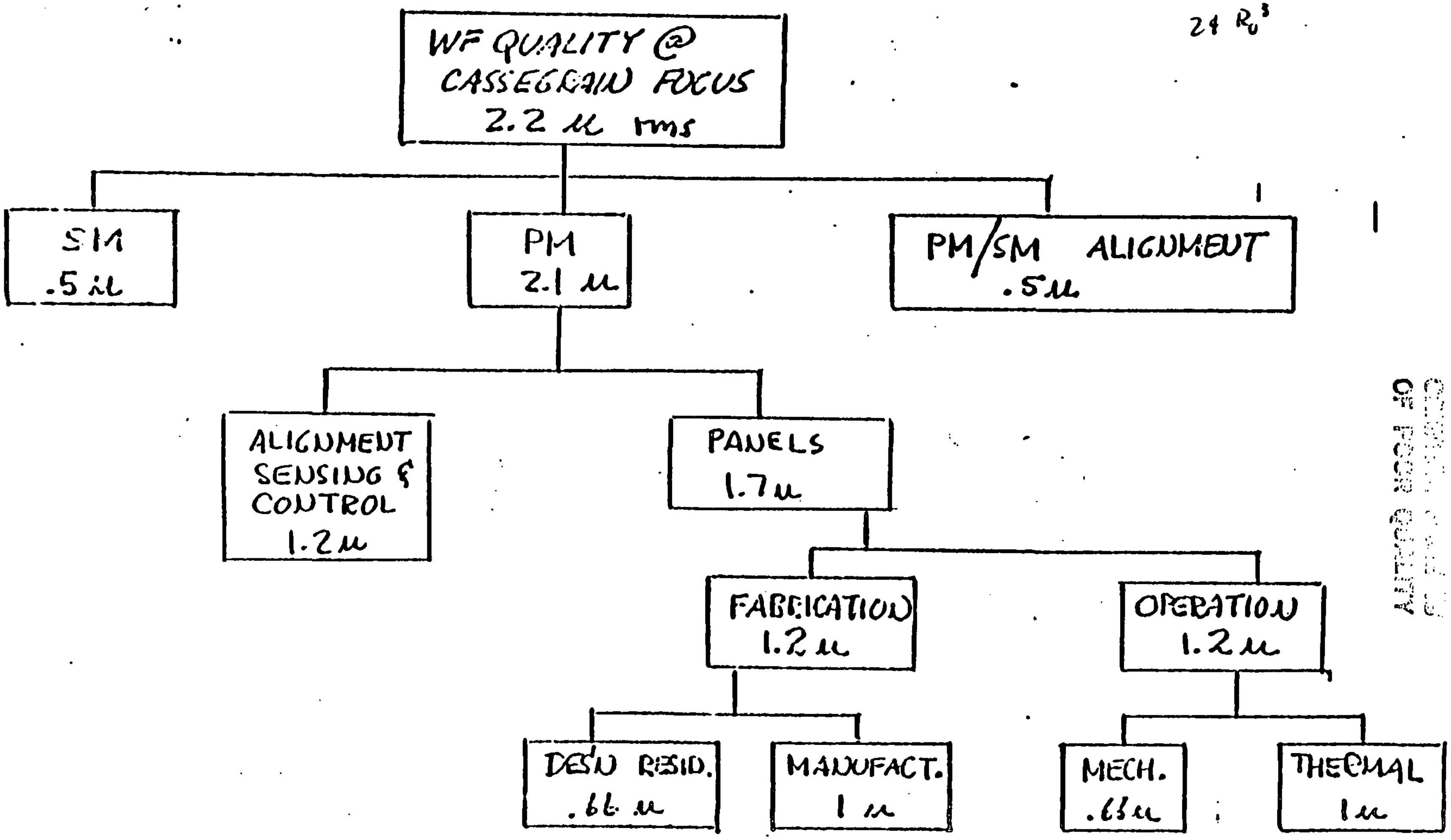
7

STATIC ERROR BUDGET

D/L PERFORMANCE ≡ $\lambda/13.7$ rms

FOR $\lambda = 30\,\mu$, $2.2\,\mu$ rms WF REQ'D

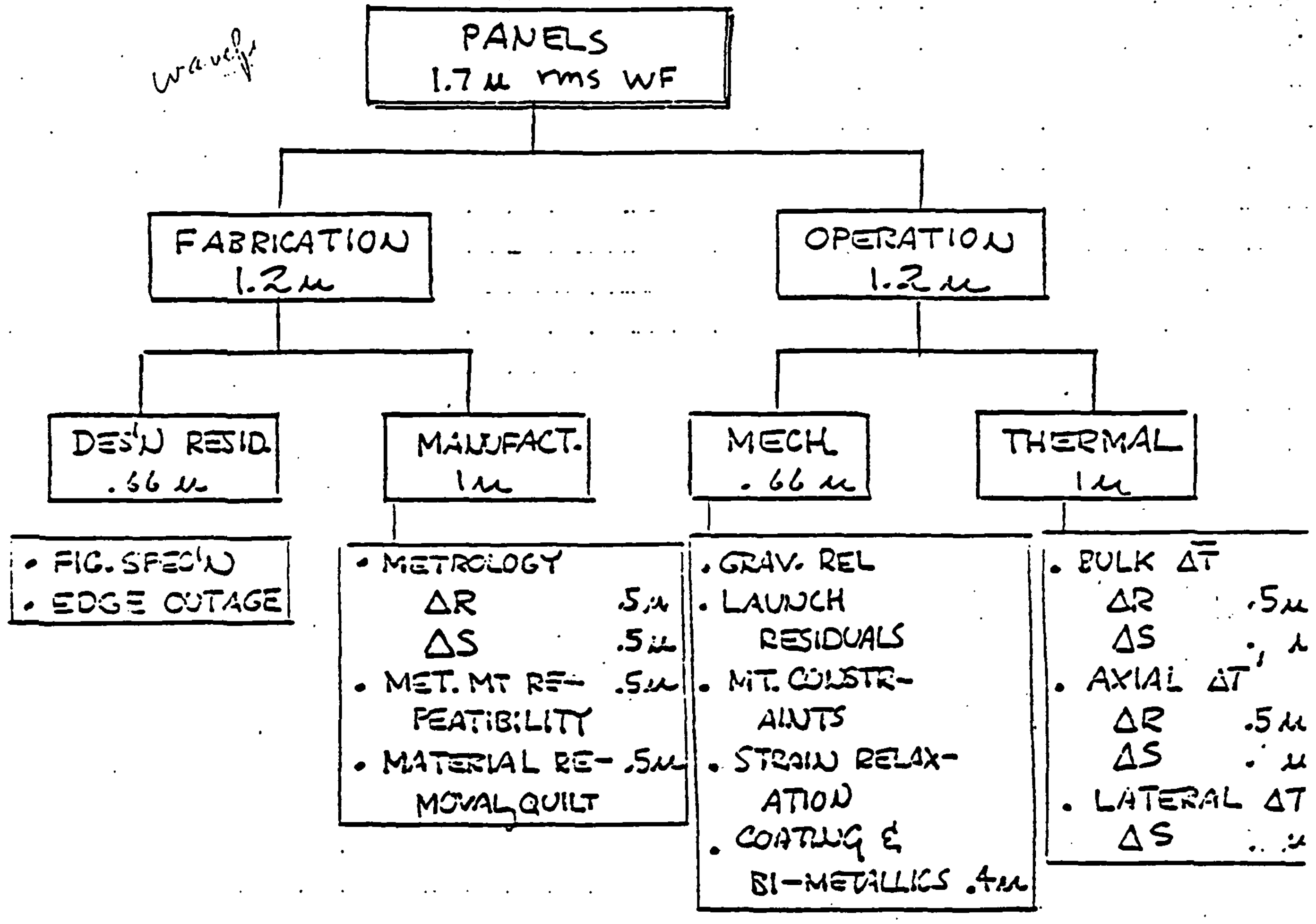
$\frac{r^4}{24 R_0^3} =$

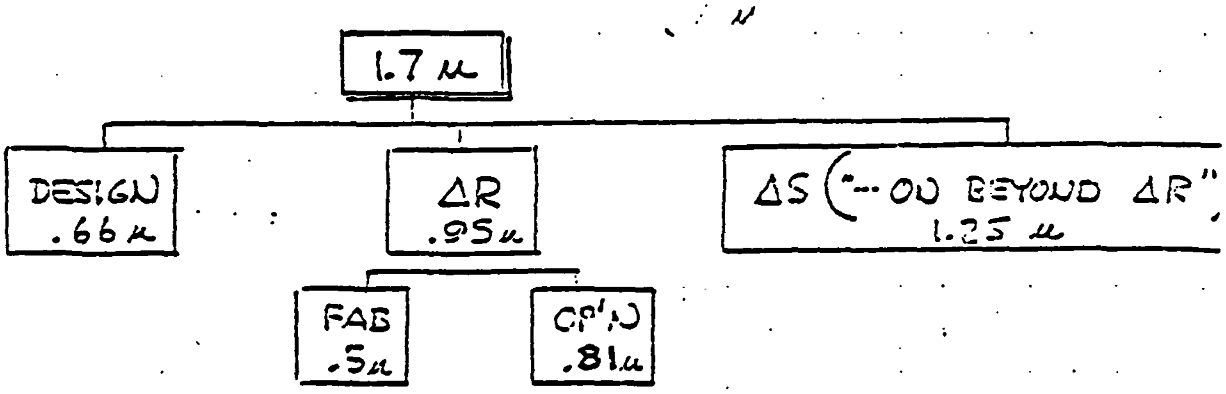


10/15/81 MK

8

SEGMENT ERROR BUDGET



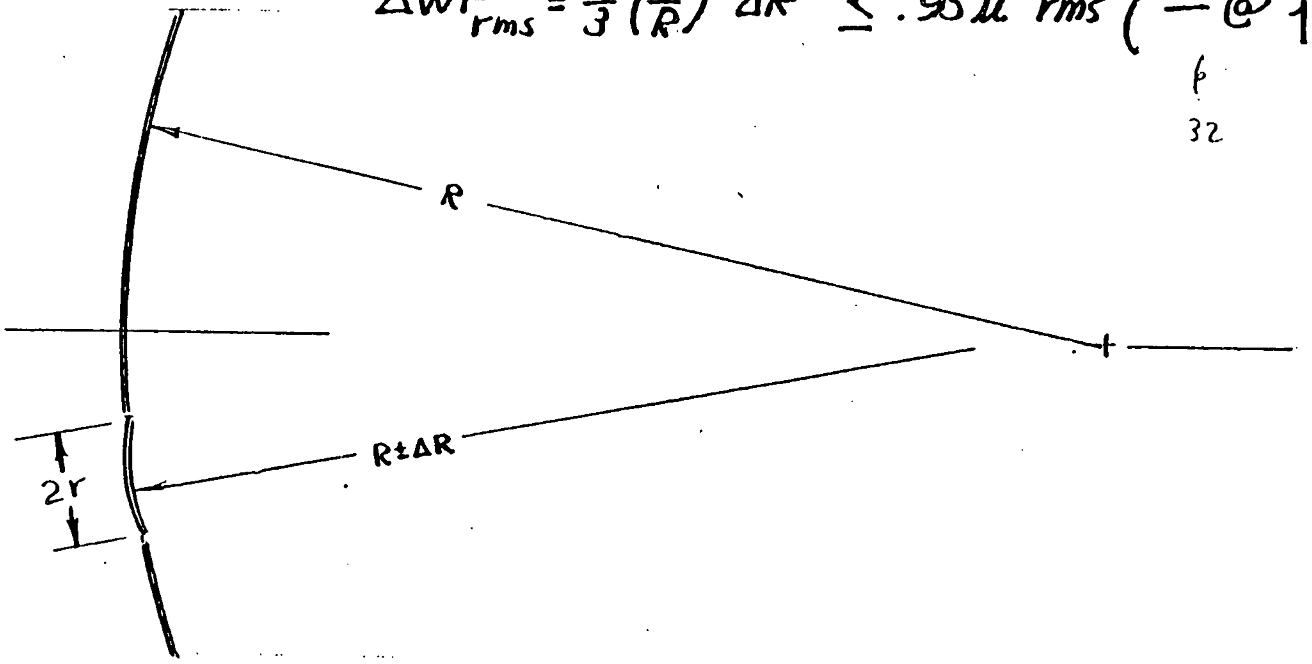


10/15/81 MK

RADIUS OF CURVATURE PRECISION:

THE ΔR ISSUE for COHERENT APERTURES

$$\Delta WF_{rms} \cong \frac{1}{3}\left(\frac{r}{R}\right)^2 \Delta R \leq .95\mu \text{ rms } \left(\frac{\lambda}{32} @ \lambda = 30\mu\right)$$



INITIAL MANUFACTURE & OPERATIONAL EFFECTS ΔR/R BUDGET

ΔR/R .000050 to .000200

~ MORE DISCUSSION LATER ~

KEY STUDY ISSUES

PASSIVE STABILITY: FIGURE & 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: SINGLEMOST DEMANDING ISSUE

- UP TO 1049 1.35 m OFF-AXIS PARABOLAS REQ'D, AS "FEW" AS 117 4m ONES
- REPLICATION/PRECISION SAGGING/FORMING/......
- NOVEL APPLICATIONS OF NON-TRADITIONAL MAT'LS

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

14

SORTING METHODOLOGY

PARAMETER	CHOICE	IMPORTANCE	ISSUES	RANKING CHOICE NO. 1	2	3	4
			"EVALUATION CRITERIA!"				
			Σ IMPORT. X RANKING =				

#5

SCORING EXPLAINATION

WEIGHTING

IMPORTANCE OF EVALUATION CRITERIA WITH RESPECT TO:

COST/PRODICIBILITY 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	"...EHH"
1	WORST

WEIGHTED RANKING

$S_W = \sum$ IMPORTANCE × RAW SCORE

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

WEIGHTING FACTORS

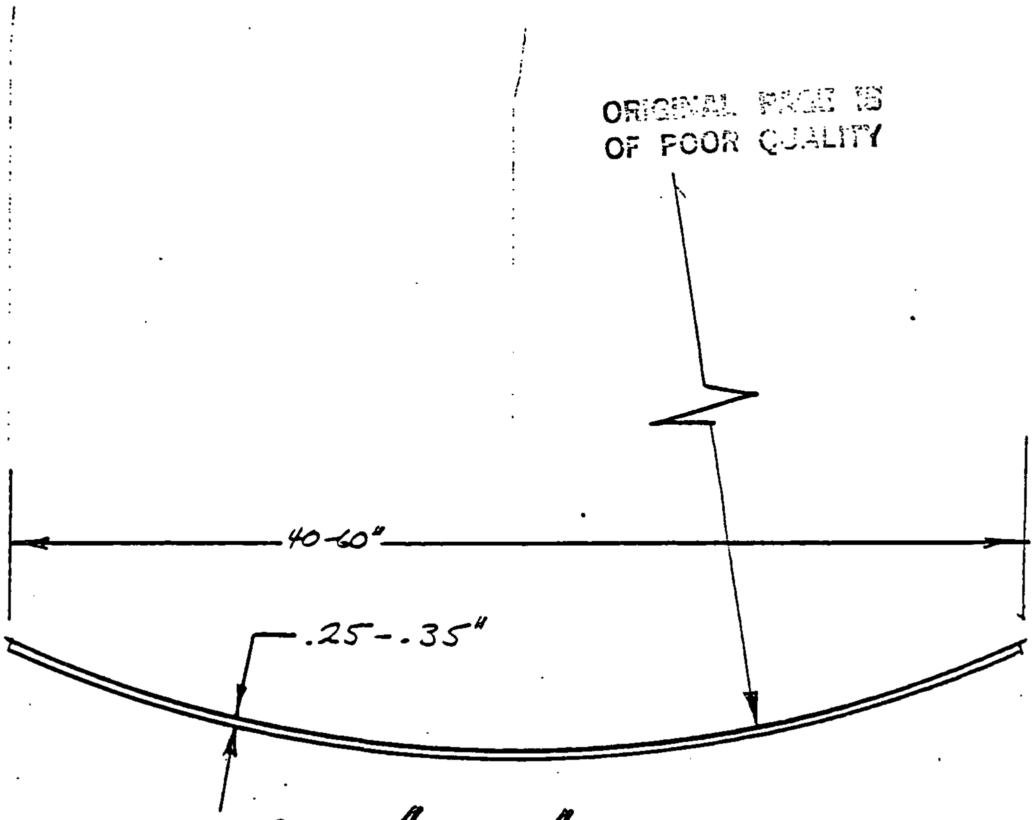
GROUND RULES

• COST	10	to	7
• PERFORMANCE	7	to	3
• PACKAGING, INTEGRATION, ENGR'G CONVENIENCE	3	to	1

EVALUATION CRITERIA RESULTS

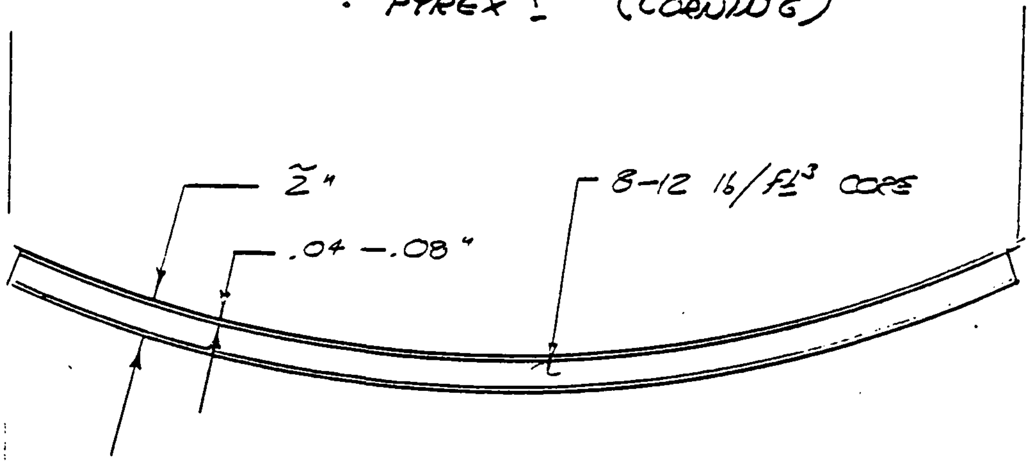
- 1-2 m PANELS PREFERABLE TO 4-m PANELS
- TRAPEZOIDS BETTER THAN HEXES
- THIN "GLASS" SHELLS & ALL-ALUMINUM SANDWICHES HAVE HIGH PAY-OFF POTENTIAL
- FUSED SILICA/QUARTZ CONVENTIONAL SANDWICHES TECHNICALLY ACCEPTABLE W/O RISK,
- BUT WE BELIEVE ARE COST-WISE PROHIBITIVE.

2 ATTRACTIVE PANEL POSSIBILITIES



SOLID "GLASS" MONOLITH

- FUSED QUARTZ (HERAEUS)
- FUSED SILICA (CORNING)
- TCC (CORNING or SCHOTT)
- PYREX ? (CORNING)

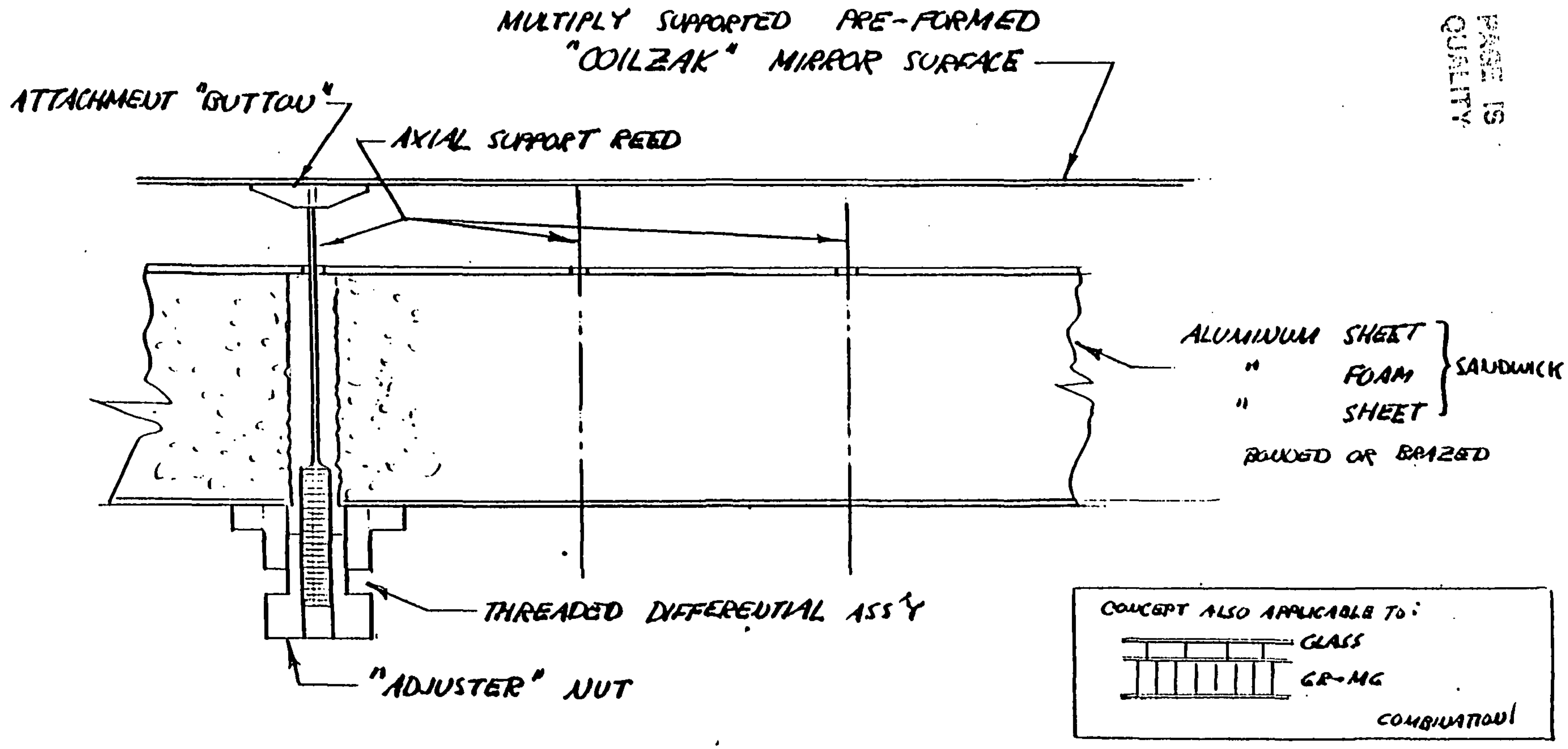


METAL/METAL SANDWICH

- ALUM. "LIGHTING SHEET" (ALCOA)
WITH FOAMED AL CORE (ERG)

HYBRID MIRROR CONCEPT

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

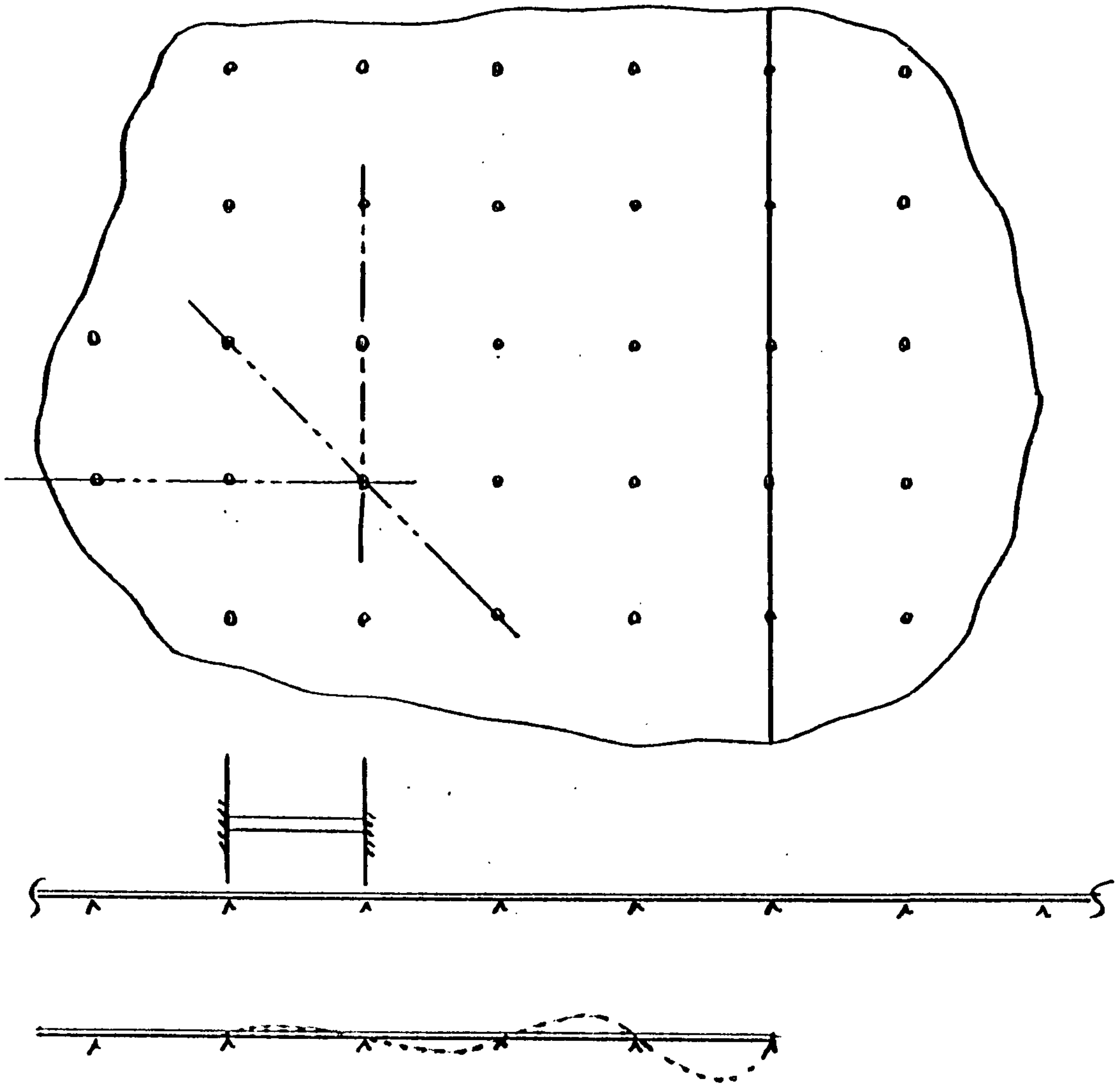


2/16/82

57

MULTIPLY SUPPORTED PLATES

THE BASIS OF HYBRID MIRRORS



INFINITE PLATE
ZERO DEFL'N

FINITE PLATE
SMALL DEFL'NS DUE
TO FINITE EDGE SLOPE

EVALUATION CRITERIA MATRIX

PARAMETER		CHOICES	WEIGHTING	EVALUATION CRITERIA	RANKING					
					a	b	c	d	e	f
• SEGMENT SHAPE	a	CIRCLE	3	NO. REQ/DIA	10	5	3	10		
	b	HEX	5	OBSCURED AREA	5	9	9	10		
	c	TRAPEZOID ✓	3	ORBITER PKG. EFFECIENCY	8	10	9	2		
	d	WEDGE	7	NO. DIFF. TOOLS REQ'D	3	3	10	10		
			7	MAT'L UTILIZATION	9	9	8	10		
			2	AVAIL. PANEL THICKNESS	10	10	9	1		
			8	PRODUCIBILITY RISK	10	10	10	1		
					213	274	305	236		
• SEG. SIZE	a	1.35 ✓	5	EDGE CURL	10	3	1			
	b	2	5	OBSCURED AREA	8	10	8			
	c	4	3	ORBITER PKG. EFFECIENCY	/	/	/			
			2	AVAIL. PANEL THICKNESS	10	5	3			
				NO. REQ'D / DIA						
			7	NO. ACTUATORS	1	3	10			
			5	SENSING, CONTROL ELEC	5	7	10			
			3	SUP'T STR. COMPLEXITY	5	7	10			
			3	ERECTABILITY	/	/	/			
			10	MAT'L & PROCESS COMPAT	10	7	4			
			10	PRODUCIBILITY RISK	10	7	4			
			5	NATURAL FREQ	10	2	1			
			7	THERMAL	10	4	1			
			7	GRAV. RELEASE	10	2	1			
			7	RELIABILITY 617, 414, 335	10	10	5			22

22

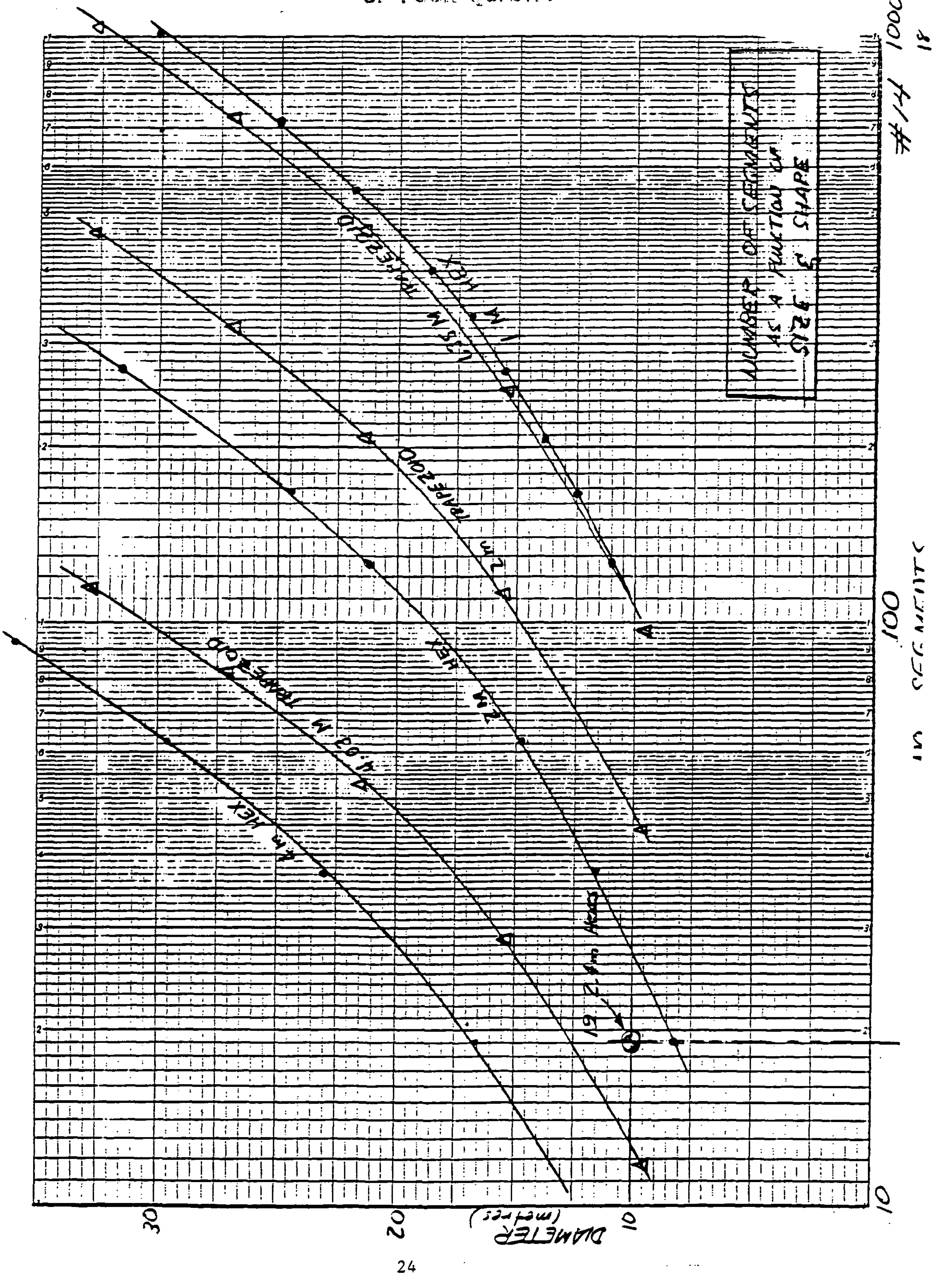
PARAMETER	CHOICES	WEIGHTING	EVALUATION CRITERIA	a	b	c	d	e	$
• SEGMENT MATERIAL	a FUSED SILICA, QUARTZ		THERMAL DISTORTION INDEX						
	b GLASSY CERAMICS ✓	5	$\rho C_p \alpha / K$	10	8	5	2	2	
	c ALUMINUM ✓	5	α / K	10	7	7	1	3	
	d GR-EP COMPOSITES		DYNAMIC EFFEC. INDEX						
	e PYREX	5	E/ρ^3	5	5	3	10	2	
		5	ISOTROPY	10	10	9	1	8	
		5	HOMOGENEITY	10	9	10	5	8	
		4	NON-POROSITY	10	10	8	2	10	
		5	COATING TEMP COMPAT.	10	10	10	1	10	
		5	VACUUM STABILITY	10	10	10	1	10	
		5	DIMENSIONAL STABILITY	10	10	5	1	1	
		10	AVAILABILITY	7	5	10	10	10	
		10	COST	1	5	10	7	7	
		7	FORMABILITY	1	5	10	8	5	
		3	SWL GROWTH POTENTIAL	10	8	1	1	2	
				532	544	597	339	411	

PARAMETER		CHOICES		WEIGHTING	EVALUATION CRITERIA	a	b	c	d	e	f
• STR'L CONFIG'N	a	THIN SOLID 'GLASS'	✓	9	REPLICABILITY	7	/	7	9	/	10
	b	SANDWICH 'GLASS'		3	QUILTING	10	1	10	10	5	10
	c	THIN SOLID ALUM.		5	DYN. EFFECIENCY	1	8	1	10	5	9
	d	SANDWICH ALUM	✓	5	CURVATURE STABILITY	10	5	10	5	/	8
	e	RIBBED		5	EDGE CURL	5	10	1	5	/	10
	f	HYBRID	(✓)	5	GRAV. RELEASE	8	10	8	10	8	10
				10	COST	2	1	10	5	/	3
				3	PACKAGING EFFEC.	10	1	10	5	1	5
						263	181	323	326	83	350

SHAPE & SIZE

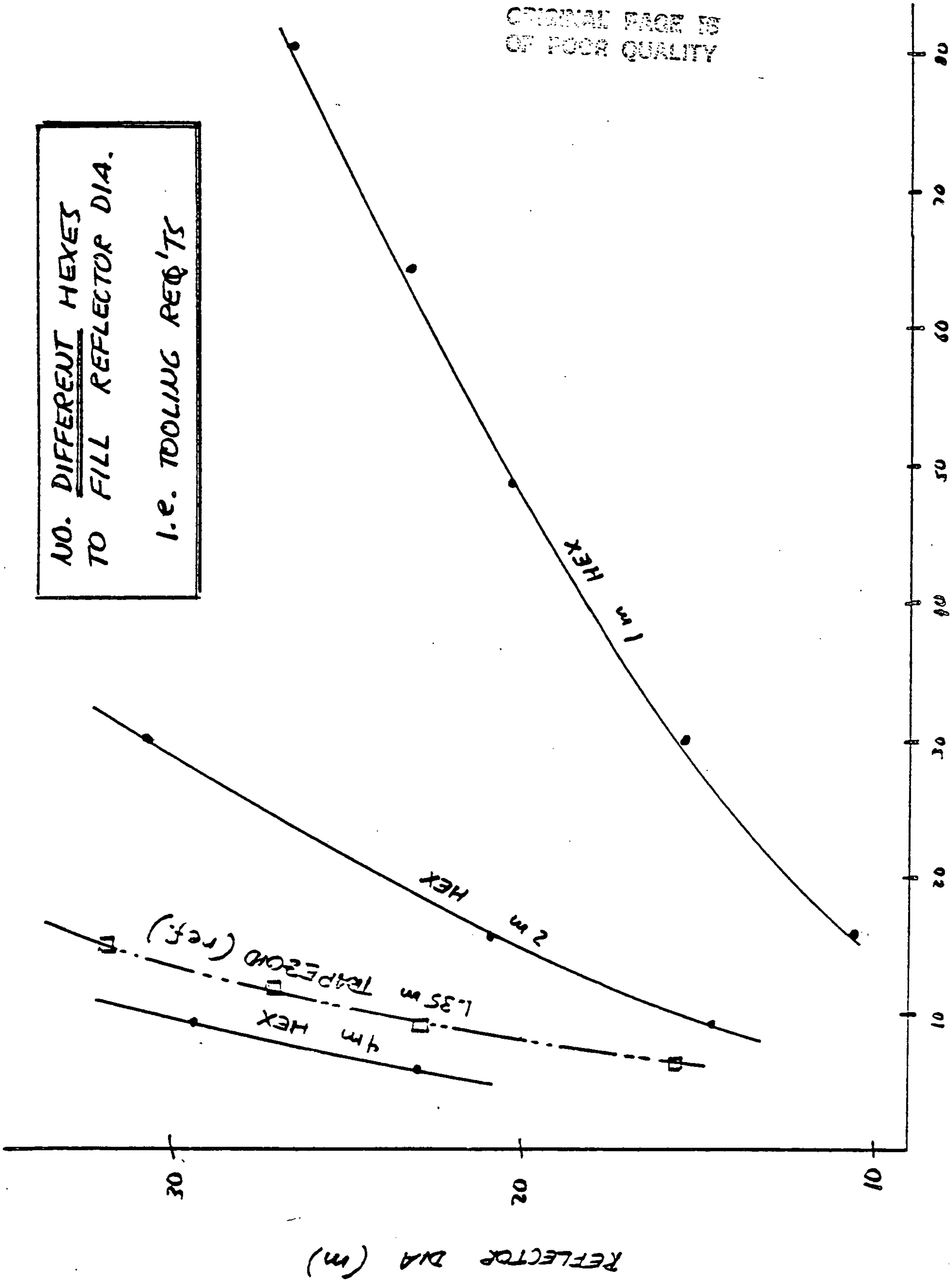
ORIGINAL PAGE IS
OF POOR QUALITY

25

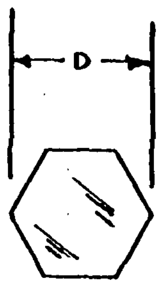


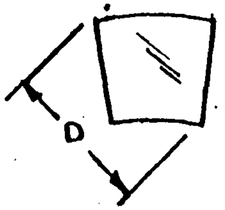
#14 18

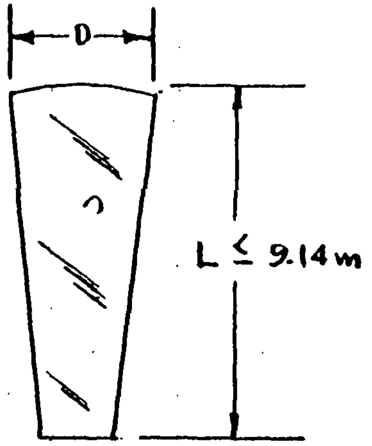
26


NO. DIFFERENT HEXES
TO FILL REFLECTOR DIA.
i.e. TOOLING REQ'TS
1m HEX
2m HEX
1.35m TRAPEZOID (ref.)
4m HEX
10
20
30
40
50
60
70
80
10
20
30
REFLECTOR DIA (m)

SEGMENT SHAPE SELECTION

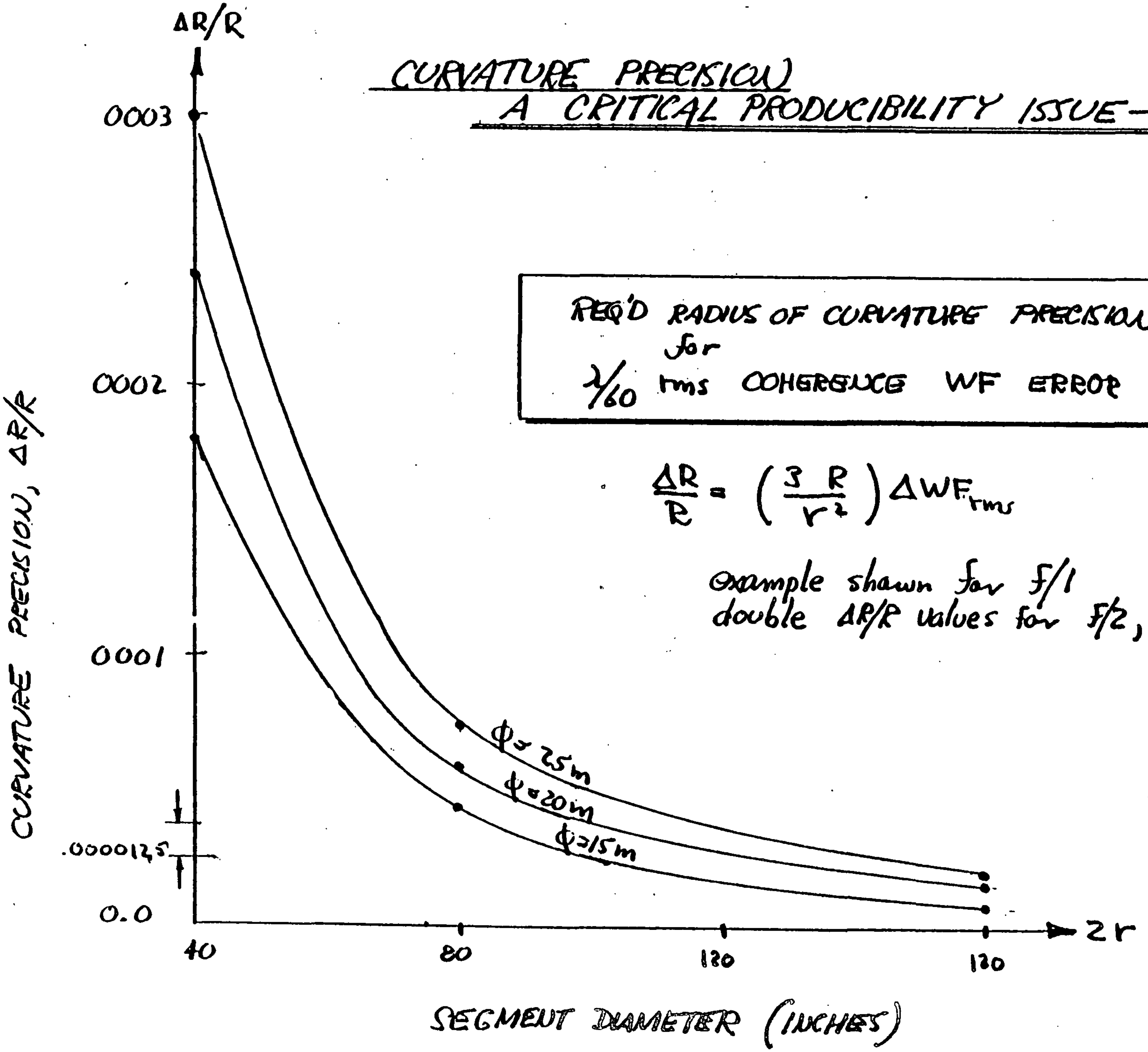






CRITERIA	HEX	"SQUARE"	WEDGE	COMMENTS *
NO. REQ'D FOR 30 m APER. WHEN D = 4m/D = 2m	61/271	117/467	32/65	
NO. DIFFERENT TYPES REQ'D	9/30	5/10	2/2	
MAX. THICKNESS @ PKG. LENGTH	.15/.1 m	.08/.08 m	0/.05 m	
NORMALIZED ALLOWABLE ΔT'	1/.67	.53/.53	0/.33	(BIG NO. BEST!)
PRODUCIBILITY ASSESSMENT	GOOD	GOOD	POOR	
ERECTABILITY FACTOR (NORMAL'ED)	1/4.4	1.9/7.7	.51/1.07	(SMALL NO. BEST!)
O'ALL PANEL COST ESTIMATE	HIGHER	LOWEST	HIGHEST/RISK	(#10) (BASED ON REPLICATION) "

CURVATURE PRECISION
A CRITICAL PRODUCIBILITY ISSUE — !



REQ'D RADIUS OF CURVATURE PRECISION
for
$\lambda/60$ rms COHERENCE WF ERROR

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

example shown for f/1
double ΔR/R values for f/2, etc

PANEL SIZE vs PERFORMANCE & MAT'L SELECTION

$$\boxed{\Delta WF_{rms} \cong \frac{1}{3}\left(\frac{r}{R}\right)^2 \Delta R}$$

$$\Delta R = \frac{R^2 \alpha \Delta T'}{h} + R \alpha \overline{\Delta T}$$

FOR A SOLID: $\Delta T' = Q \frac{h}{K}$, $\overline{\Delta T} = \frac{Q\tau}{m c_p}$ & $m \equiv \rho_A$

AFTER MANIPULATION:

$$\boxed{D = 2r \leq 2\sqrt{\frac{3\,\Delta WF \;\; R^2}{\left(\frac{R^2}{K} + \frac{R\tau}{m c_p}\right) Q \alpha}}}$$

RESULTS: $R = 1600''$, $\Delta WF = \lambda/60$, $Q = .011 \pm .0011$ B/hr in^2 , $\tau = .5$ hrs

Alum	98	312	in
TGC	64	204	
Quartz	134	404	
Pyrex	25	78	

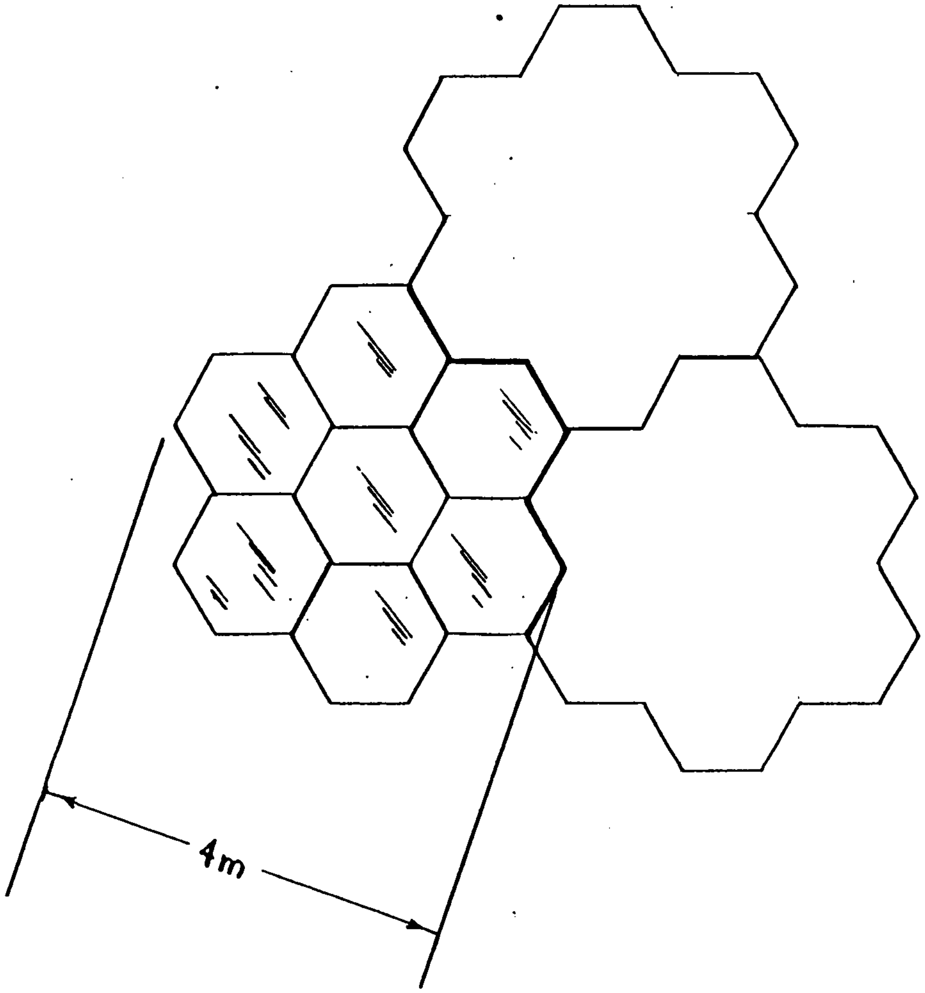
30

DYNAMICS vs PANEL SIZE for SOLIDS

$$\boxed{f = \frac{\rho_A}{2\pi}\sqrt{\frac{25 E g}{12\pi r^4 \rho^3}}}$$

MAT'L \ ρ_A	15 Kg/m²			30			45				
SEC ϕ(2r)	1	1.5	2	1	1.5	2	1	1.5	2	3	4
ALUMINUM											
$E/\rho^3 = 102,956$	14	6.3	3.5	28	12.4	7	42	18.7	11	4.7	2.8
t_{SOLID}		.21"			.4"			.64"			
TGC											
$E/\rho^3 = 130,384$	17.7	7.9	4.4	35	16	8.9	53	24	13.3		
t_{SOLID}		.23"			.46			.7"			
QUARTZ											
$E/\rho^3 = 145,945$	19.8	8.8	5	39	17.6	9.9	59	26	15		
t_{SOLID}		.26"			.54"			.81"			
PYREX											
$E/\rho^3 = 101,986$	13.8	6.13	3.4	22.7	12.3	6.8	41	18.4	10.4	4.6	2.6
t_{SOLID}											

FREQUENCY VALUES (cps)



PRE-ASSEMBLED SMALL SEGMENT MODULES

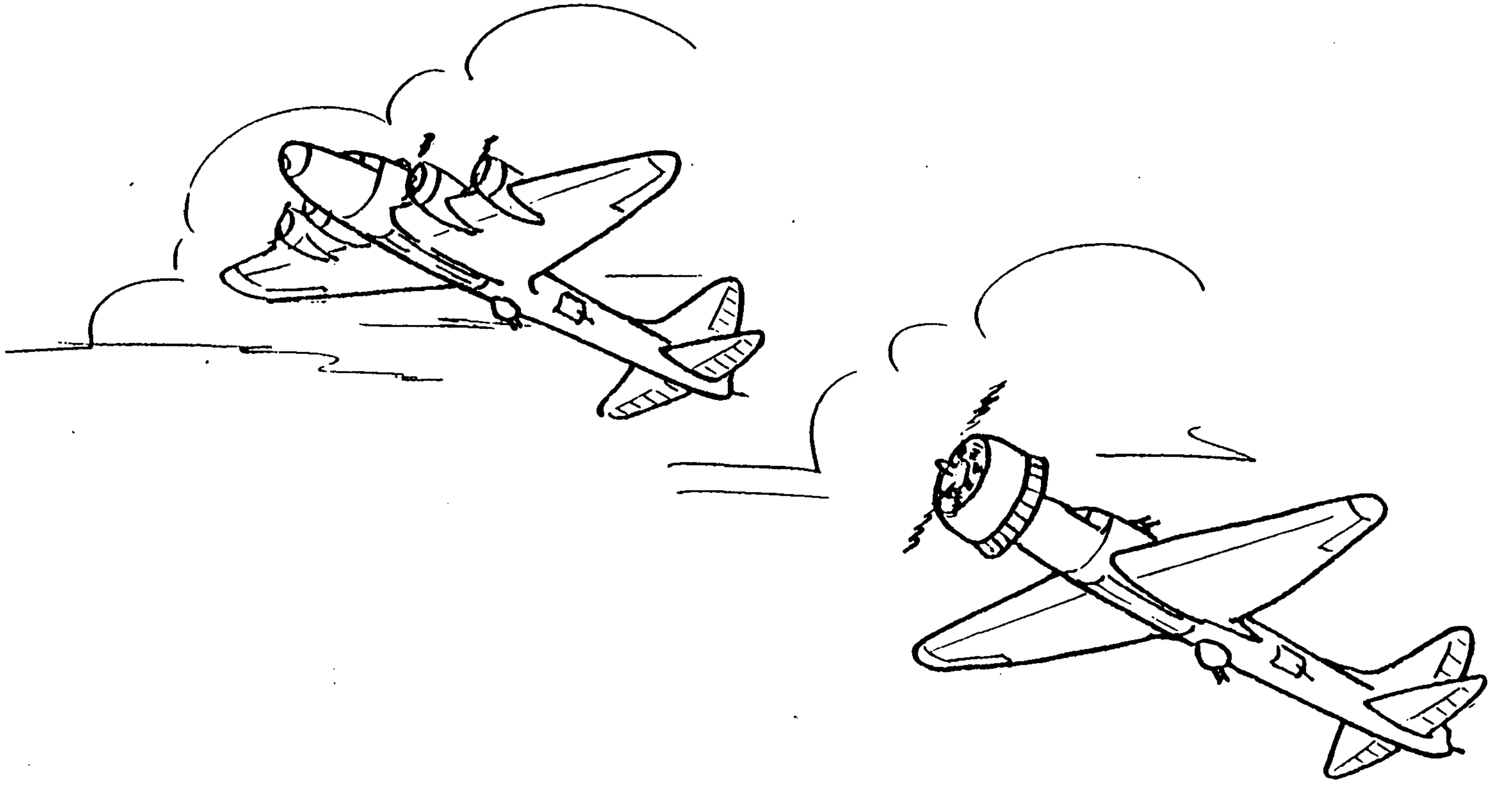
FACILITATES SMALL SEGMENT ERECTABILITY

1/14

21

KEY TRADE PARAMETERS	PANEL SIZE	
	1 – 2 m	4 m
MAT'L AVAILABILITY	YES	SCALE-UP REQ'D
PRODUCIBILITY RISK/PANEL COST PER FT^2	LOWER	HIGHER
PANEL WEIGHT/SPECIFIED FREQUENCY	LOWER	HIGHER BY 4X
THERMAL SUSCEPTIBILITY	LOWER	HIGHER BY 4X
FIGURE CONTROL SPATIAL RESOLUTION	BETTER	WORSE
ACTUATORS & CONTROLS	HIGHER COST	LOWER COST

BETTER INDIVIDUAL PANEL PERFORMANCE & COST EFFECTIVITY
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

35

E/ρ^3, A DYNAMICS PARAMETER

$$f = \frac{1}{2\pi}\sqrt{\frac{25EIg}{Wr^2}}$$

$I = t^3/12$ (in^3)
$g = 386$ in/sec^2
W = Segment weight (lbs)
E = Modulus of Elasticity (lb/in^2)
r = Segment radius (in)

$W = \rho_A \pi r^2$ where ρ_A is AREAL DENSITY (lb/in^2)

$I \equiv t^3/12$

$$f = \frac{1}{2\pi}\sqrt{\frac{25Et^3g}{12\rho_A\pi r^4}}$$

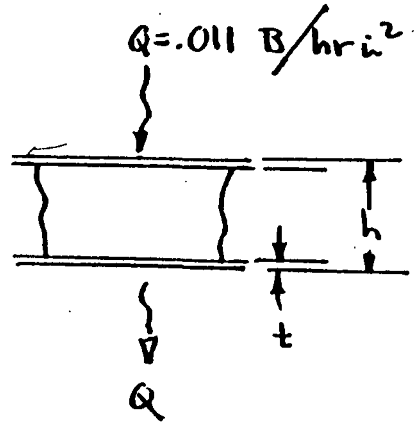
Also $\rho_A = \rho t$ for solid mirrors or $t^3 = \frac{\rho_A^3}{\rho^3}$

$$\boxed{f = \frac{1}{2\pi}\sqrt{\frac{25E\rho_A^{2\cancel{3}}g}{12\cancel{\rho_A}\pi r^4\rho^3}}}$$

23

SOLID/SANDWICH THERMAL TRADE SUMMARY

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



STEADY STATE MODEL

K= 8.33 B/hr in F° (alum.)

t=.05

N=.07 (12 lb/ft³ core)

h	ΔT/h
1	.0171 °F/in
2	.0180
3	.0183
4	.0184
0 (SOLID)	.0013

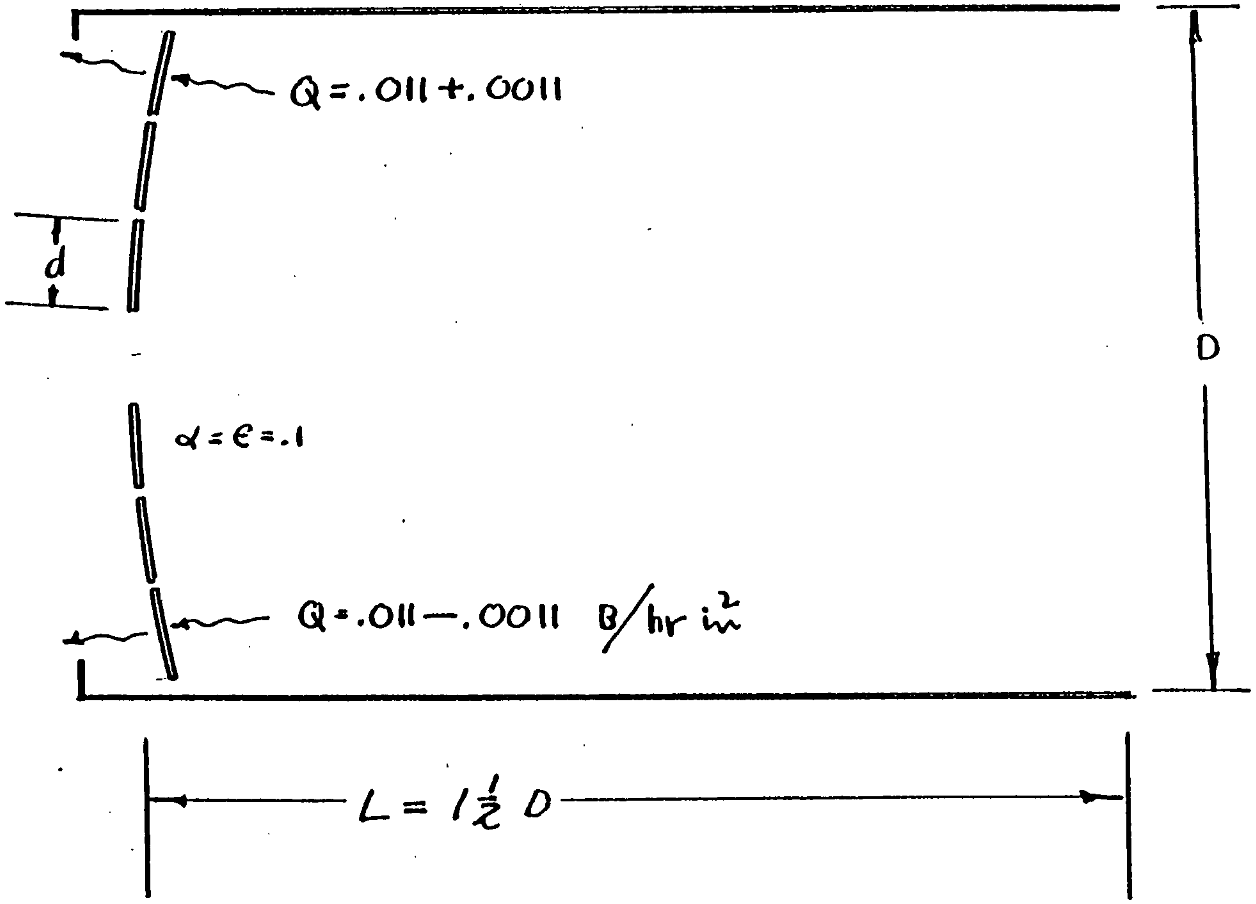
$$\Delta R = R^2 \alpha \left(\frac{\Delta T}{h}\right)$$

SOLIDS ARE THERMALLY MORE STABLE

ALUM EXAMPLE SHOWN, SIMILAR CONCLUSIONS FOR "GLASSES"

THERMAL ANALYSIS RESULTS SUMMARY*
for
STATIC AXIAL GRADIENT ASSESSMENT

$d << D$ ∴ $\tilde{\text{NO}}$ LATERAL GRADIENTS IN SEGMENT

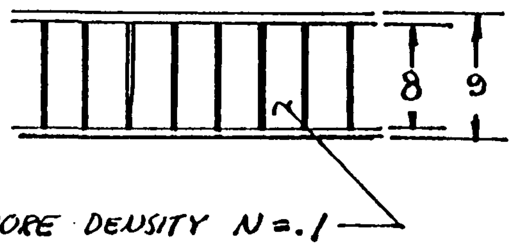


* DETAILS IN THERMAL ANALYSIS SECTION

FUSED SILICA/QUARTZ SANDWICH

2.4 m CONVENTIONAL MIRRORS "OK"

$\rho_A = 100$ Kg



CTE @ 200 °K

CORNING FUSED SILICA	$.16 \times 10^{-6}$ in/in/°F	
HERAEUS " QUARTZ	$.08 \times 10^{-6}$	

K (CONDUCTIVITY) .067 B/hr in °F

- $$\Delta T = Q \frac{\left[2t\left(1-\frac{1}{N}\right)+\frac{h}{N}\right]}{K}$$ (NEGLECTING RADIATION HEAT X-FER)

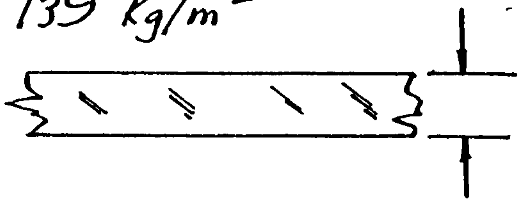
$\Delta T/h = .17$ °F/in WHEN $\Delta Q = .0011$ B/hr in^2 (10% SIDE-TO-SIDE FLUX VARIATION)

- $\Delta R/R = R\alpha \frac{\Delta T}{h}$ & FOR R = 1200" (i.e. 15m f/1):

CORNING	$\Delta R/R = .000033$	OK for 2.4 m SEGMENTS
HERAEUS	$\Delta R/R = .000016$	

FUSED SILICA/QUARTZ SOLIDS

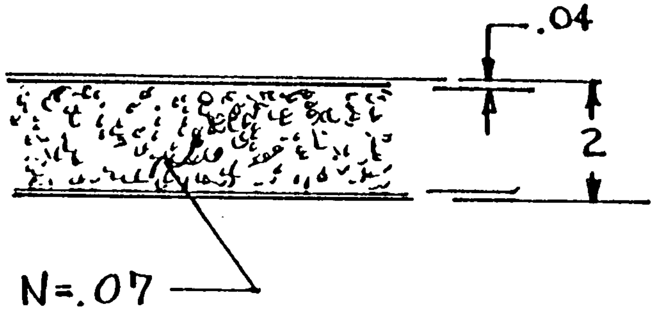
$\rho_A = 139\ Kg/m^2$



$$\frac{\Delta T}{h} = \frac{Q}{K} = \frac{.0011}{.067} = .016\ °F/in$$ (10x BETTER THAN S'WICH!)

$$\frac{\Delta R}{R} = 1200 \times .16 \times 10^{-6} \times .016 = 3.1 \times 10^{-6}$$

ALUMINUM SANDWICH / STEADY STATE GRADIENT



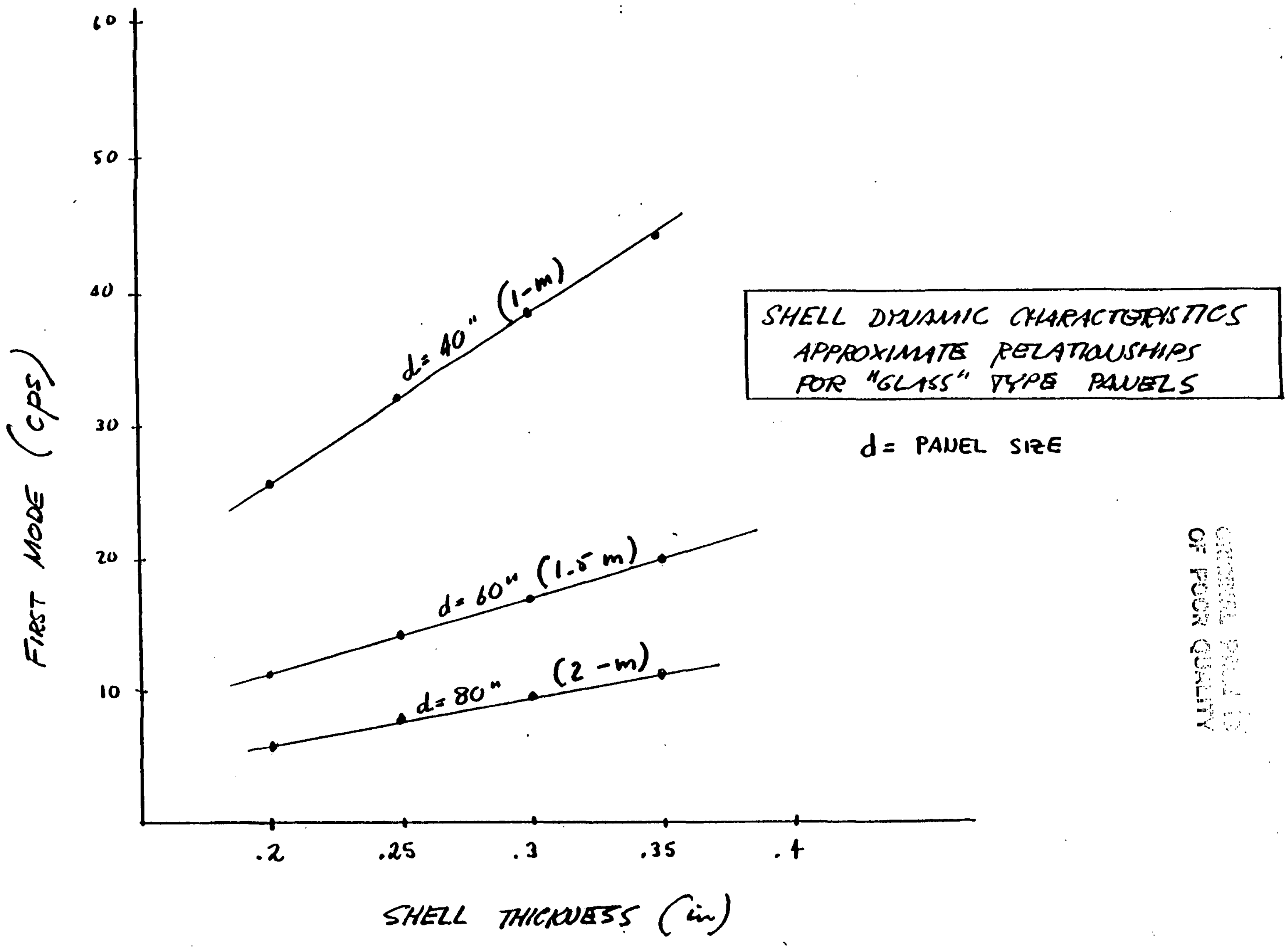
$CTE \cong 12 \times 10^{-6}$ in/in/°F

$K = 8$ B/hr in °F

$$\frac{\Delta T}{h} = .0019 \ {}^{\circ}F/in$$

$$\frac{\Delta R}{R} = 1200 \times 12 \times 10^{-6} \times .0019 = .000027$$

UP TO 80" (2-m) PANELS OK !



SHELL DYNAMIC CHARACTERISTICS
APPROXIMATE RELATIONSHIPS
FOR "GLASS" TYPE PANELS

d = PANEL SIZE

4

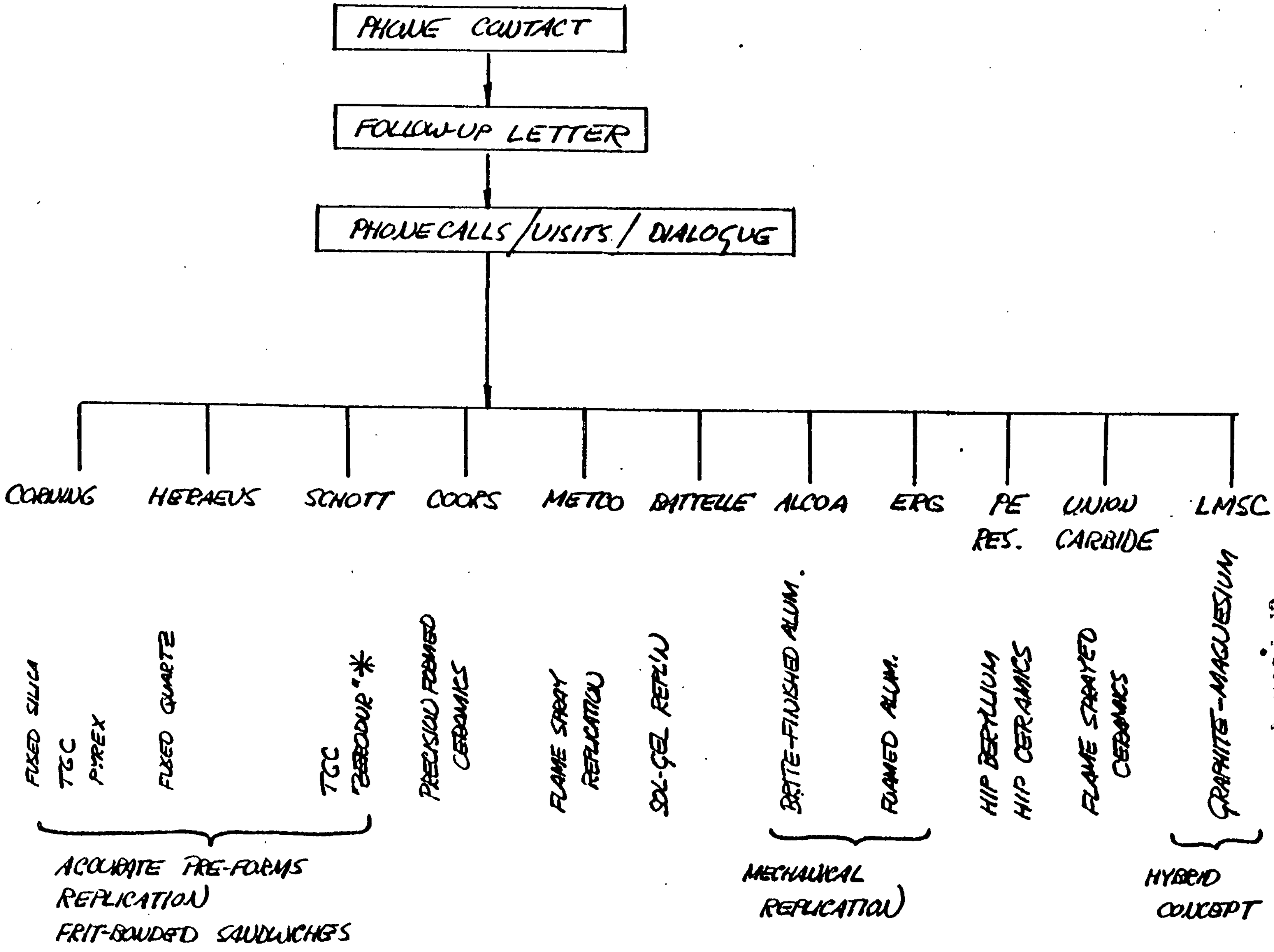
CONCLUSIONS

- SMALL PANELS
  - LESS COSTLY
  - LESS TECHNICAL RISK
  - MORE ACTUATORS
    - ESTIMATED COST TRADE STILL FAVORABLE
    - OFFERS ADD'L FIGURE CONTROL POTENTIAL
- TRAPEZOIDAL SHAPE
  - FAVORS REPLICATION AND/OR ACCURATE PREFORMS
  - BETTER STREHL
- TRANSPARENT GLASSY CERAMICS or ALUMINUM
  - EXPLOITATION OF "COMMON" MATERIALS
  - BOTH ARE "REPLICABLE"
  - GOOD CANDIDATES FOR DEVELOPMENT PROGRAM
- SOLIDS (GLASS) & SANDWICHES (ALUMINUM)
  - COMPATIBLE WITH "SMALL", REPLICABLE, & PRODUCIBILITY CHARACTERISTICS OF SELECTED MAT'LS

TASK 2

CURRENT TECHNOLOGY ASSESSMENT

POTENTIAL SUPPLIER CONTACTS



* DARPA TECHNOLOGY @ PE

CORNING

- TRANSPARENT GLASS CERAMIC # 9618

E	$11.2\ e^6$ lb/in^2	
ρ	$.09$ lb/in^3	
α	$.013 \times 10^{-6}$ in/in/°F	(0-300°C)

CTE IS TAILORABLE TO FAVOR ~200°K OPERATING TEMP

- SAGGABLE & CAN BE VACUUM FORMED

DIE FORMING w/GRAPHITE OR SiO_2 FORMS TO BE INVESTIGATED

- BASICALLY AN INEXPENSIVE MAT'L, ITS USED FOR RANGE-TOPS!

HERAEUS

- "OPTASIL" FUSED QUARTZ
- HAS BEEN PRECISION FORMED BETWEEN GRAPHITE DIES

  25,000 Å SMOOTHNESS

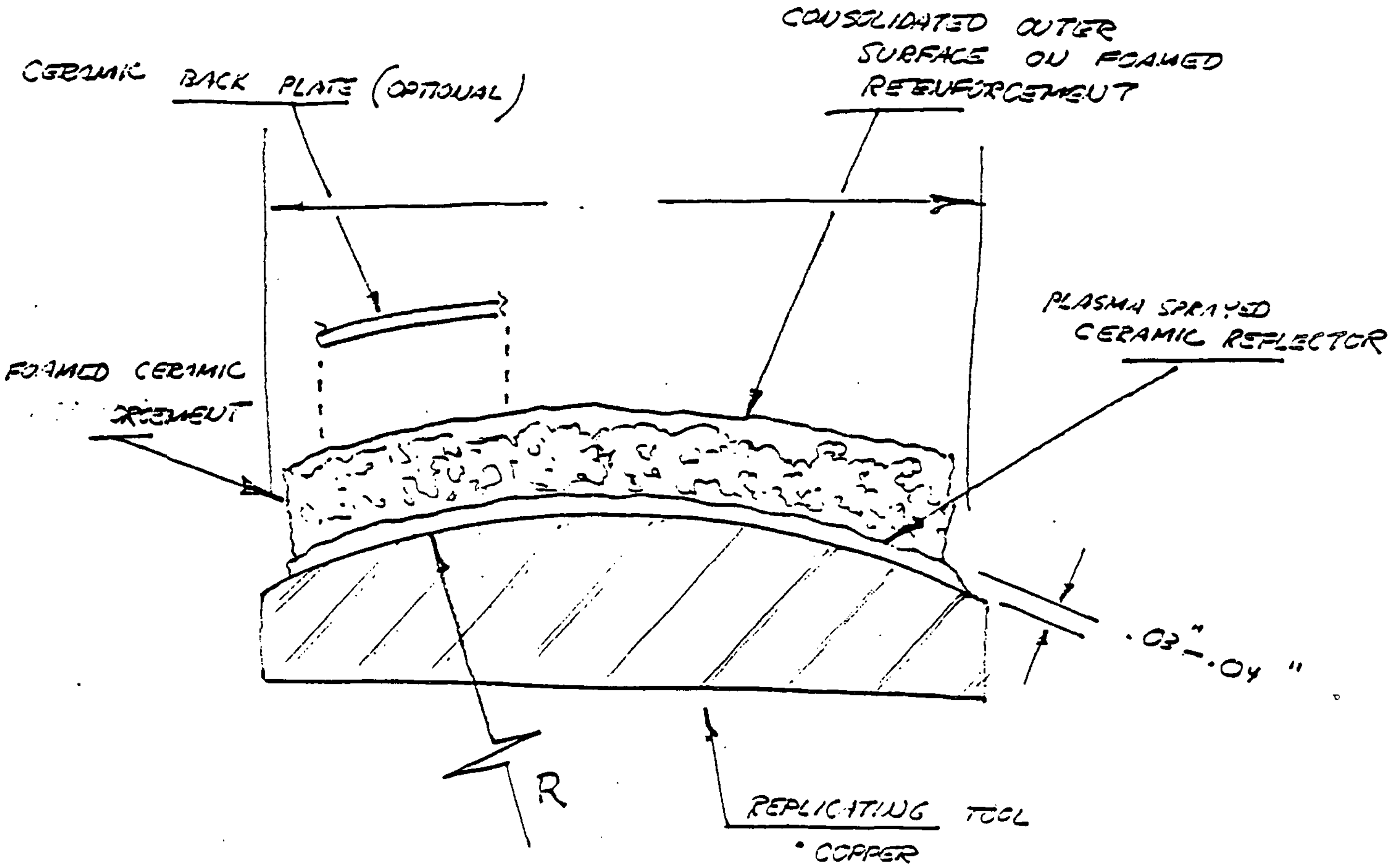
  COULD BE POLISHED TO 2000-3000 Å LDR REQ'T
- COST IS \$13,300 FOR A 1-m SHELL IN QUANTITIES OF 1000.
- COULD BE PRODUCED @ 2 PER WEEK
- O'ALL SHAPE ERROR $\leq$ 10 μ in TO BE VERIFIED

<u>METCO</u> (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

ORIGINAL PAGE IS OF POOR QUALITY



- COPPER
- FINISHED TO OPTICAL PRESCRIPTION AND SMOOTHNESS
- MAY BE SACRIFICIALLY REMOVED BY ETCHING IF REQ'D

- DIAMETER 40 < D < 60 inches
- RADIUS OF CURVATURE 300 < R < 2400 inches
- " " " TOLERANCE 300 ± .025, 2400 ± .132 inches
- OVERALL SURFACE ACCURACY 15×10^{-6} inches rms
- SMOOTHNESS 4×10^{-6} inches rms
- QUANTITY REQ'D UP TO 1000

REPRESENTATIVE PARAMETERS

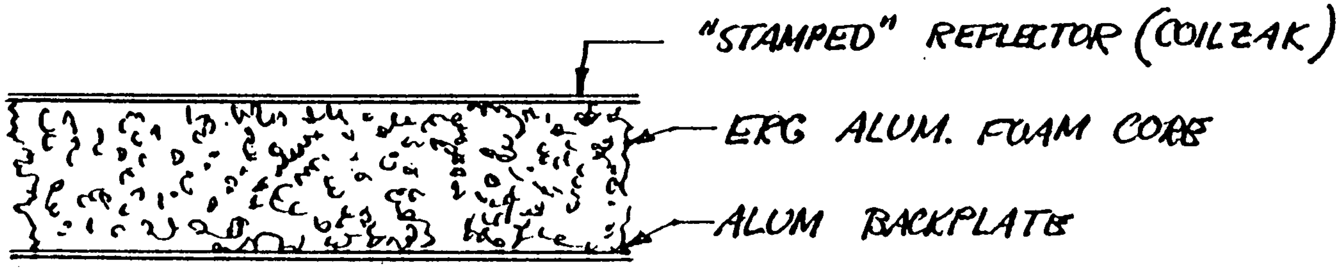
ALCOA/ERG

- ULTRA-SMOOTH ALUMINUM LIGHTING SHEET COILZAK (R)
- FOAMED ALUMINUM CORE MAT'L

SMOOTHNESS 1000 ± 500 Å rms

REFLECTIVITY GOOD W/ GOLD OVERCOAT

- HOLDS PROMISE FOR VERY INEXPENSIVE PANELS IN THE 1 TO $1\frac{1}{2}$ m SIZE RANGE



⇒ ALL-ALUMINUM MECHANICALLY REPLICATED PANEL
NO FIGURING OR POLISHING REQ'D

(MORE INFO. IN SUBS. SECTION)

Jr

SUCCESS CRITERIA for ALUMINUM SANDWICHES

$\Delta WF_{rms} = \frac{\lambda}{60} = .5\,\mu$ BUDGET

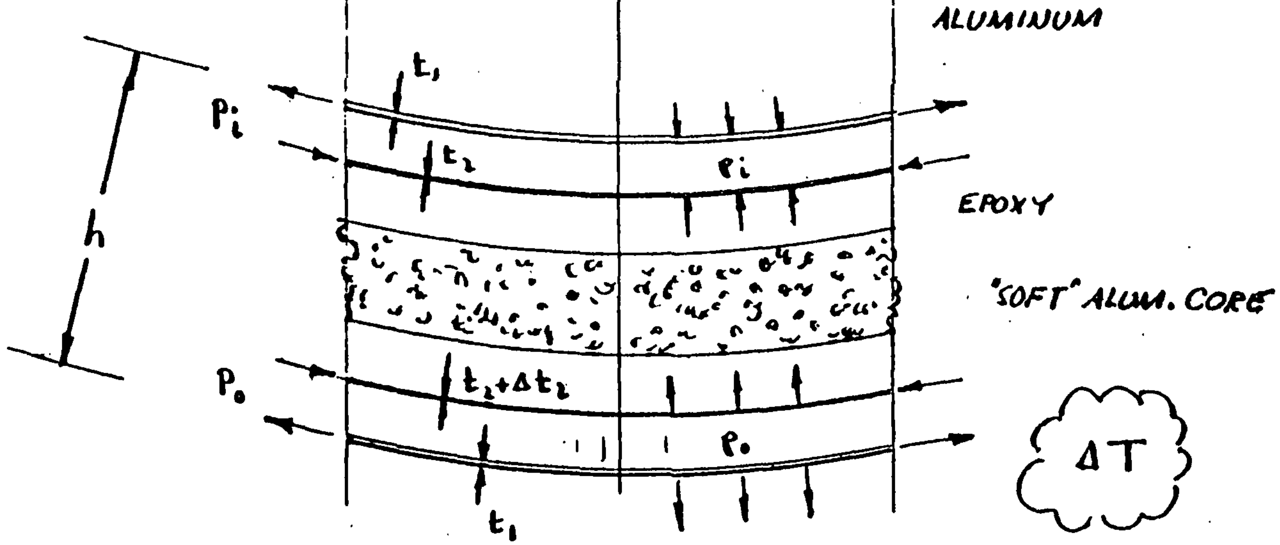
$\Delta WF_{rms} = \frac{1}{2}\,\Delta_{P-P}$ (from $\Delta WF = \frac{1}{3}\left(\frac{r}{R}\right)^2 \Delta R$)

$\therefore\ \Delta_{P-P} \cong 40 \times 10^{-6}$ in (i.e. $1\,\mu$)

IF ALL SEGMENTS WITHIN A 20°F RANGE

$$\boxed{\Delta_{P-P}/°F = 2 \times 10^{-6}}$$

ALL-ALUMINUM SANDWICH MECHANICS



$$M = P_o \frac{t_1+t_2+\Delta t_2}{2} - P_i \frac{t_1+t_2}{2}$$

AFTER SOLVING FOR P_o & P_i

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

AND

$$\Delta_T = \frac{Mr^2}{2EI} = \frac{Mr^2}{E t_1 h^2} \quad \text{in P-P}$$

THERMAL BENDING SENSITIVITY

ALL-ALUM SANDWICH , $\Delta t_2 = t_2$

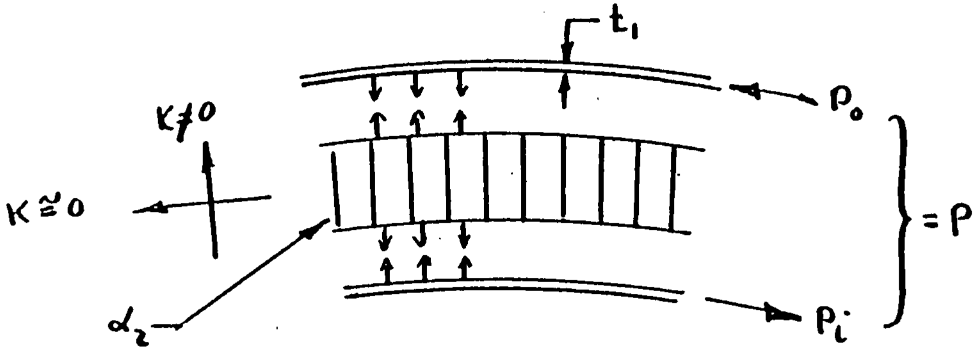
		SEGMENT DIA.			
h	$t_2 \setminus a$	1m	2m	3m	4m
.5 in.	.004 in	4.9×10^{-6}	19.6×10^{-6}	44.1×10^{-6}	78.4×10^{-6}
	.006	7.6	30.4	68.4	122
	.008	10.4	41.6	93.6	166
.75	.004	2.16	8.6	77.4	35
	.006	3.36	13.4	30.2	54
	.008	4.6	18.4	41.4	74
1	.004	1.21	4.8	10.9	19.4
	.006	1.89	7.6	17.	30
	.008	2.61	10.4	23.5	42
1.25	.004	.8	3.2	7.2	12.8
	.006	1.21	4.84	10.9	19.4
	.008	1.67		15.	27
1.5	.004	.54	2.16	4.86	8.6
	.006	.84	3.36	7.56	13.4
	.008	1.16	4.64	10.4	18.6
2	.004	.3	1.2	2.7	4.8
	.006	.47	1.9	4.23	7.5
	.008	.65	2.6	5.9	10.4

Δ_{P-P}/°F (inches)

← ACCEPTABLE REGION $\Delta_{P-P}/°F < 2\ \mu in/°F$

COMPARISON WITH GR-EP/AL. HONEYCOMB PANEL

- COMPOSITE PANEL



$$M = \frac{h^2(\alpha_2 - \alpha_1)\, t_1\, E_1}{2R(1-\nu)}$$

$$\left.\begin{array}{l} h = 1.5 \\ t_1 = .04 \\ E_1 = 15 \times 10^6 \\ R = 1600 \\ \Delta\alpha = 12 \times 10^{-6} \end{array}\right\} M = .0051 \text{ in-lb/in/°F}$$

- FOR $h = 1.5$ & $t_1 = .04$ & $t_2 + \Delta t_2 = 2t_2$ ALL ALUM. MIRROR

$$M = .0012 \text{ in-lb/in/°F}$$

INDUCED BENDING MOMENT LESS IN ALL-ALUM MIRROR!

TASK 3

IDENTIFY & EVALUATE PRIME TECHNOLOGIES

C-3

WHY WE SELECTED THE ALUMINUM SANDWICH FOR THE EXPERIMENT

CANDIDATE LDR-TYPE MIRRORS

CANDIDATE	COMMENTS
FUSED SILICA, FUSED QUARTZ SANDWICHES	TOO EXPENSIVE FOR LDR BUT IT WOULD DEFINITELY WORK
FUSED SILICA, FUSED QUARTZ THIN SOLIDS	(SEMI-)REPLICABLE BUT VERY EXPENSIVE AND VERY LONG LEAD TIMES
LITHIUM ALUM. SILICATE *1 THIN SOLIDS	AWAITING CORNING & SCHOTT DATA, A DEFINITE MAYBE!
PYREX THIN SOLID	CTE'S TOO HIGH & K'S TOO LOW, BUT ITS CHEAP & REPLICABLE
✓ COILZAK ® *2 ALUM SANDWICH	WE THINK ITS REPLICABLE & STABLE ENOUGH & CHEAP!!!
COILZAK ® MULTIPLY SUPPORTED ON Gr-Mg	TOO DEPENDANT ON DEVELOPMENT OF STABLE GRAPHITE-MAGNESIUM
MACHINED "ALUMINUM" CASTING	TOO EXPENSIVE VIS À VIS FIGURING LABOR
GR-EP SANDWICH (AL. OR NOMEX CORE)	COILZAK AL-AL SANDWICH IS LESS THERMALLY SENSITIVE !
HIP BERYLLIUM	TOO EXPENSIVE FOR LDR BUT IT WOULD WORK
METCO FLAME SPRAYED XXX REPLICAS	A LONG SHOT, MAY HAVE BIG PAYOFF, EMBRYONIC STAGE

* PREBRIGHTENED ALCOA ALUM LIGHTING SHEET, ~1000 Å SMOOTHNESS

*1 CORNINGWARE PRECURSOR GLASSY CERAMIC

COST ESTIMATE EXAMPLE

DIRECT COSTS, NO FEE, etc !!!

WAG ONLY

HERAEUS 1-m PANELS

QUANTITY	COST EACH	
1	$95,500	
7	38,800	ASSUME 22,000 IN THE 250-750 QUANTITY RANGE
1000	13,300	

DELIVERY RATE: 2 per WEEK

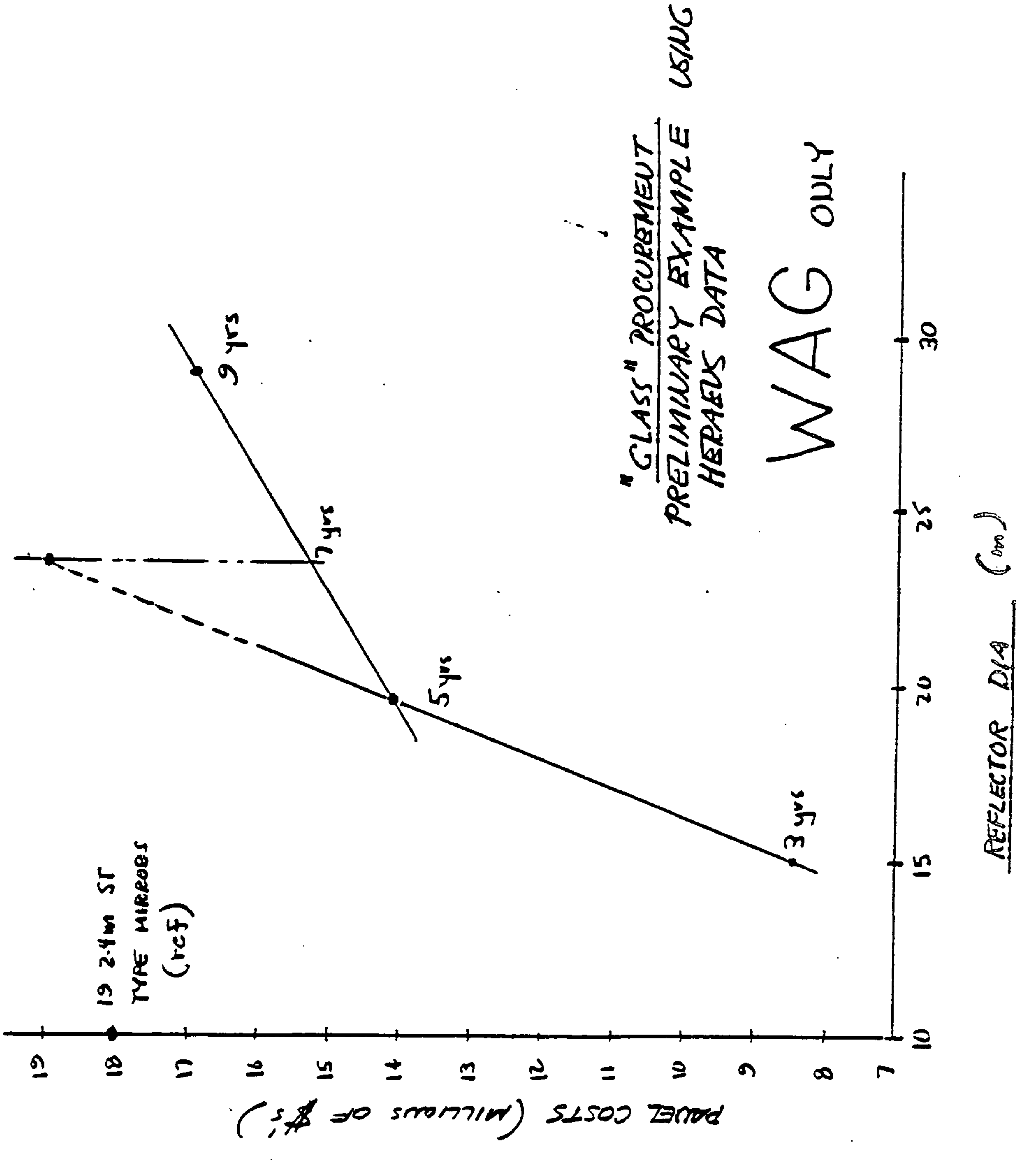
SHAPE	REFLECTOR DIA. (m)			
	15	20	25	30
TRAPEZOID	353	628	981	1413
HEX	271	483	754	1086

NO. PANELS REQ'D
CUT FROM 1-m CIRCULAR BLANK

COST ESTIMATE (CONT'D) WAG ONLY

PROCUREMENT CYCLE	NO. 1-m PANELS DEL.	COST*	REFLECTOR SIZE ☐ PANELS	 ⬡ PANELS
3 yrs	312	$\$8.4e^{6}$	14.1 m	16.1 m
5 yrs	520	$13.9e^{6}$	18.2	21
7 yrs	728	e^{6}	21.5	24.6
9 yrs	936	$16.9e^{6}$		29

*INCL. 120 hrs/panel to SMOOTH FROM 25,000 to 2000 Å


"GLASS" PROCUREMENT
PRELIMINARY EXAMPLE USING
HERAEUS DATA
WAG ONLY
9 yrs
7 yrs
5 yrs
3 yrs
19 2.4m ST
TYPE MIRRORS
(ref)
PANEL COSTS (MILLIONS OF $'s)
7
8
9
10
11
12
13
14
15
16
17
18
19
REFLECTOR DIA (000)
10
15
20
25
30

ACTUATOR COSTS & PANEL SIZE TRADE

No. Blanks Req'd $N \cong \left(\frac{D}{d}\right)^2$

D = REFL. DIA
d = PANEL DIA

No. Actuators Per Panel = 6

Reflector Cost $\cong \left(\frac{D}{d}\right)^2 \left[B + 6A\right]$

B = Blank Cost
A = Actuator Cost

4m	$B \cong 2.5\,e^6$	FUSED SILICA S'WICH
2m	$B \cong .7\,e^6$	" " "
1m	$B = 13{,}300$	FUSED QT'Z SHELL

ACTUATOR "BREAK-EVEN" COSTS
\$25,000 → 36,000 each

I THINK THEY WILL COST LESS !! PROBABLY MUCH LESS !!

~ SMALLER PANELS WILL BE MORE COST EFFECTIVE ~

60

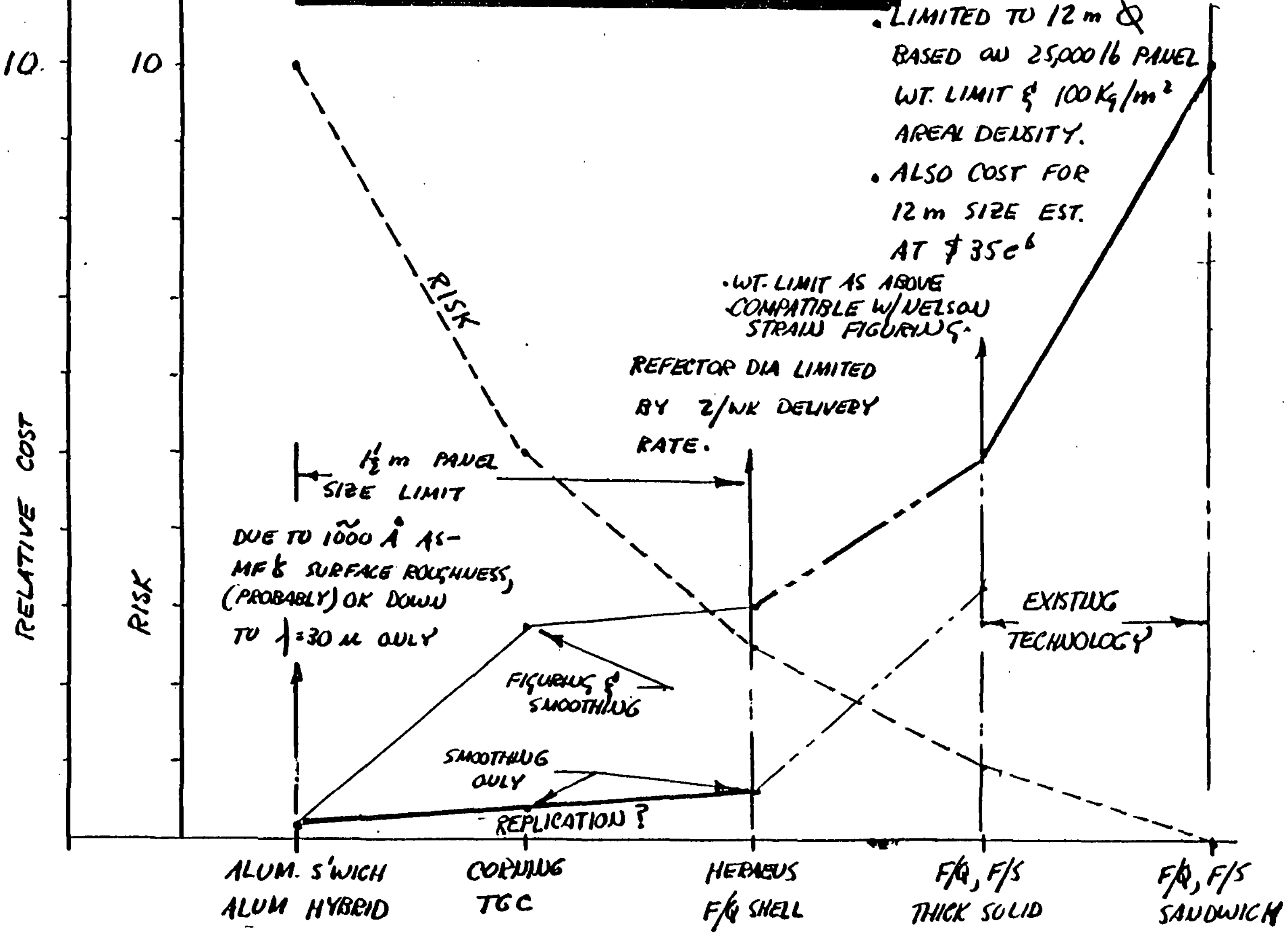
TO BE DONE

- DEFINE ACTUATOR REQ'TS
- ESTIMATE ACTUATOR COSTS
  - DEVELOPMENT THRU QUAL
  - RECURRING
- CONFIRM BREAK-EVEN POINT CONCLUSIONS

W1

PANEL COST/RISK SUMMARY

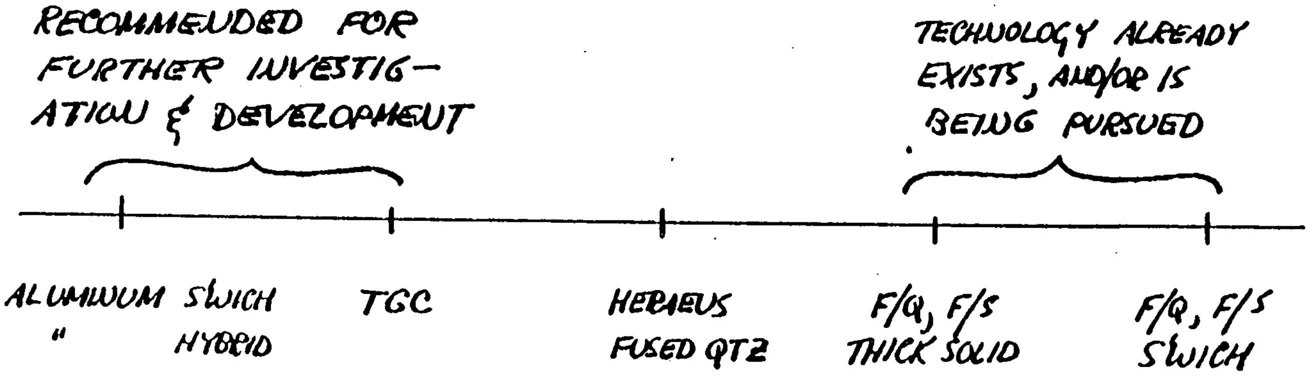
TODAY'S ASSESSMENT



7/22/82

RECOMMENDED CANDIDATES FOR CONTINUED DEVELOPMENT

2/25/82



RECOMMENDED FOR FURTHER INVESTIGATION & DEVELOPMENT

TECHNOLOGY ALREADY EXISTS, AND/OR IS BEING PURSUED

ALUMINUM S'WICH " HYBRID	TGC	HERAEUS FUSED QTZ	F/Q, F/S THICK SOLID	F/Q, F/S S'WICH

- JOINING MAT'L:
  FILLED EPOXY
  GALLIUM-ALUM
- FORMING ACCURACY

- MAT'L CHARACTERIZATION WORK,
- MOLDING PROCESSESS,
- 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. RUTHVEN

STRUCTURAL/MECHANICAL TREND STUDIES

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

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

②

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 BY "CLOSED-FORM SOLUTION" CORRELATION.
- HIGHER ORDER ANALYSIS EMPLOYED "BASELINE MODEL" MODIFIED FOR INVESTIGATION OF SEVERAL PARAMETER CHANGES (I.E., BOUNDARY CONDITIONS, F/NO's, ETC.)
- THIS MODIFICATION ENTAILED MESH REFINEMENT OF THE (+) (+) SEGMENT QUADRANT

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

CATALOG OF TEST MODELS

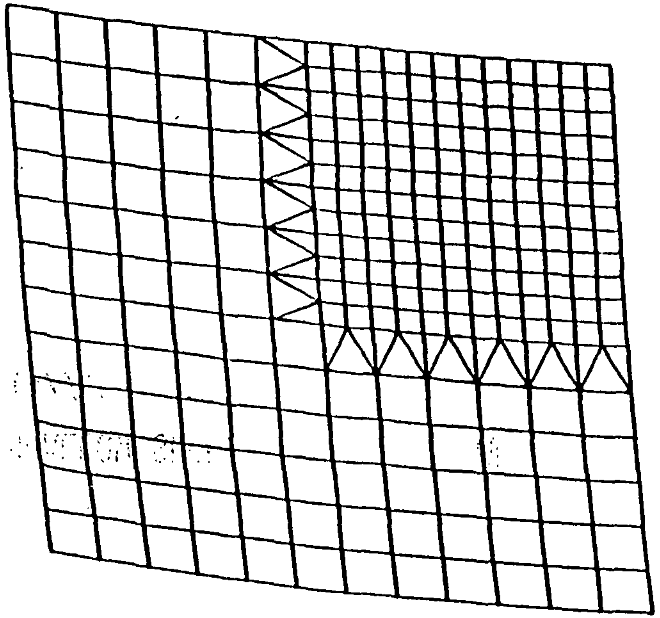
MODEL NAME*	NO. OF NODES	NO. OF ELEMENTS	NO. OF D.O.F.
4M-4 NODE	81	64	486
4M-6 NODE (BASELINE MODEL)	169	144	1014
4M-12 NODE	289	276	1734
4M-24 NODE	433	564	2598
2M-12 NODE	79	75	474

*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

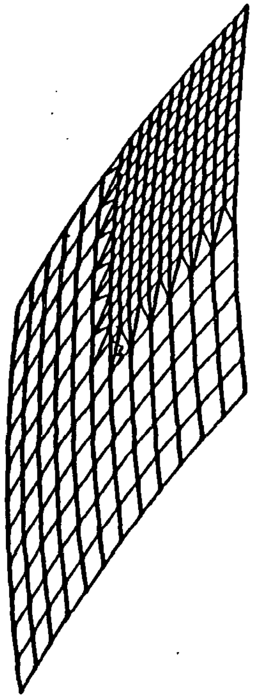
④

4M-12NODE LDR MODEL PLOTS

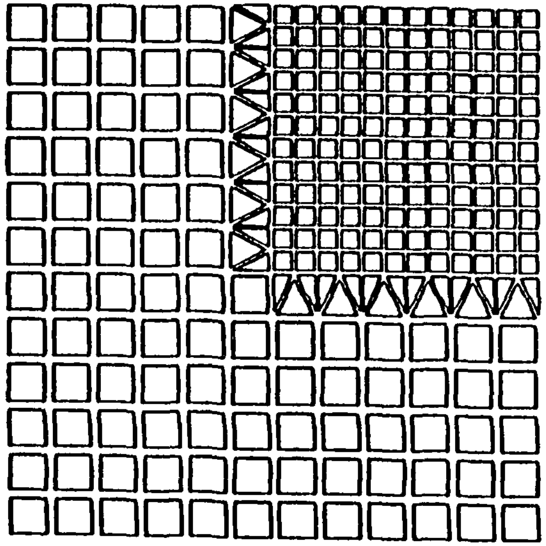


NODE/ELEMENT CONNECTIVITY

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



SKEWED PLOT TO SHOW INITIAL
RADIUS OF CURVATURE



ELEMENT "SHRINK" OPTION

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

MODEL VERIFICATION RESULTS

- ALL CORRELATIONS USED THE "BASELINE MODEL"

MODEL CONFIGURATION	BOUNDARY CONDITION	LOAD CONDITION	% DISCREPANCY FROM CLOSED-FORM SOLUTION
FLAT PLATE	CENTER NODE CONSTRAINED (STATICALLY DETERMINATE)	THRU-THE THICKNESS THERMAL GRADIENT	0.00
FLAT PLATE	CLAMPED-CLAMPED	POINT LOAD @ CENTER NODE	0.80
SHALLOW SHELL (F/7.5)	MULTIPLY SUPPORTED	THRU-THE-THICKNESS THERMAL GRADIENT	0.00

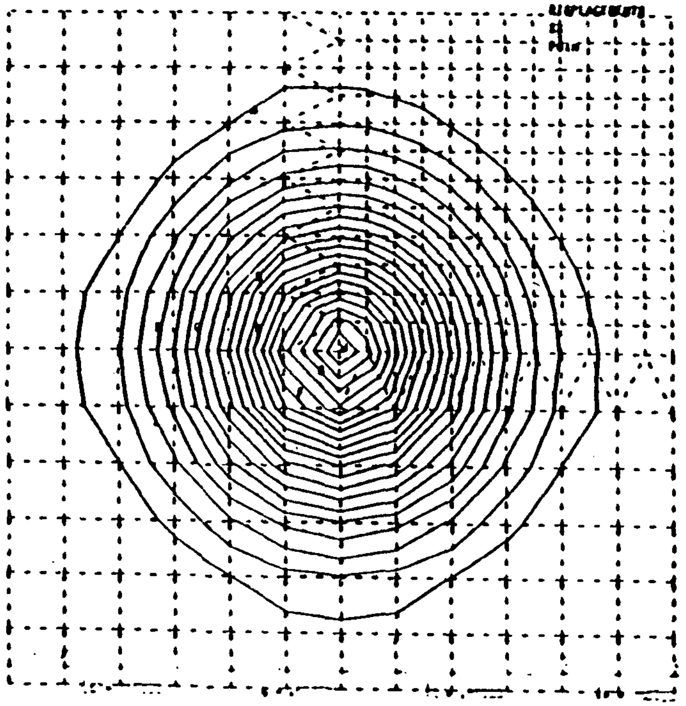
G.P.R. - 2/25/82

⑥

MODEL VERIFICATION PLOTS

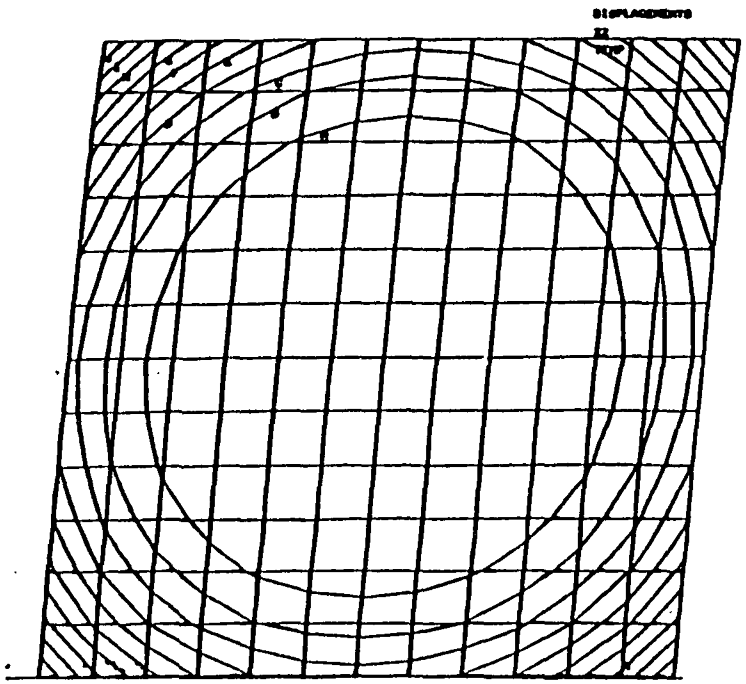
(LATERAL* DIRECTION DISPLACEMENTS)

- CLAMPED-CLAMPED FLAT PLATE
  POINT LOAD @ CENTER



δ_{MAX} = 2.45 INCHES

- STATICALLY DETERMINATE FLAT PLATE
  TRANSVERSE THERMAL GRADIENT



δ_{MAX} = 2.87E-4 INCHES

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

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

⑦

APPLICABLE SEGMENT F/NO's

SEGMENT F/NO

SEGMENT DIA. (METERS)	APERTURE (METERS)					
	30M		20M		15M	
	F/1.0	F/.5	F/1.0	F/.5	F/1.0	F/.5
4M	7.5	3.75	5.0	2.5	3.75	1.875
2M	15.0	7.5	10.0	5.0	7.5	3.75
1M	30.0	15.0	20.0	10.0	15.0	7.5
	R_C=60M	R_C=30M	R_C=40M	R_C=20M	R_C=30M	R_C=15M

NOTE: R_C → RADIUS OF CURVATURE

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

⑧

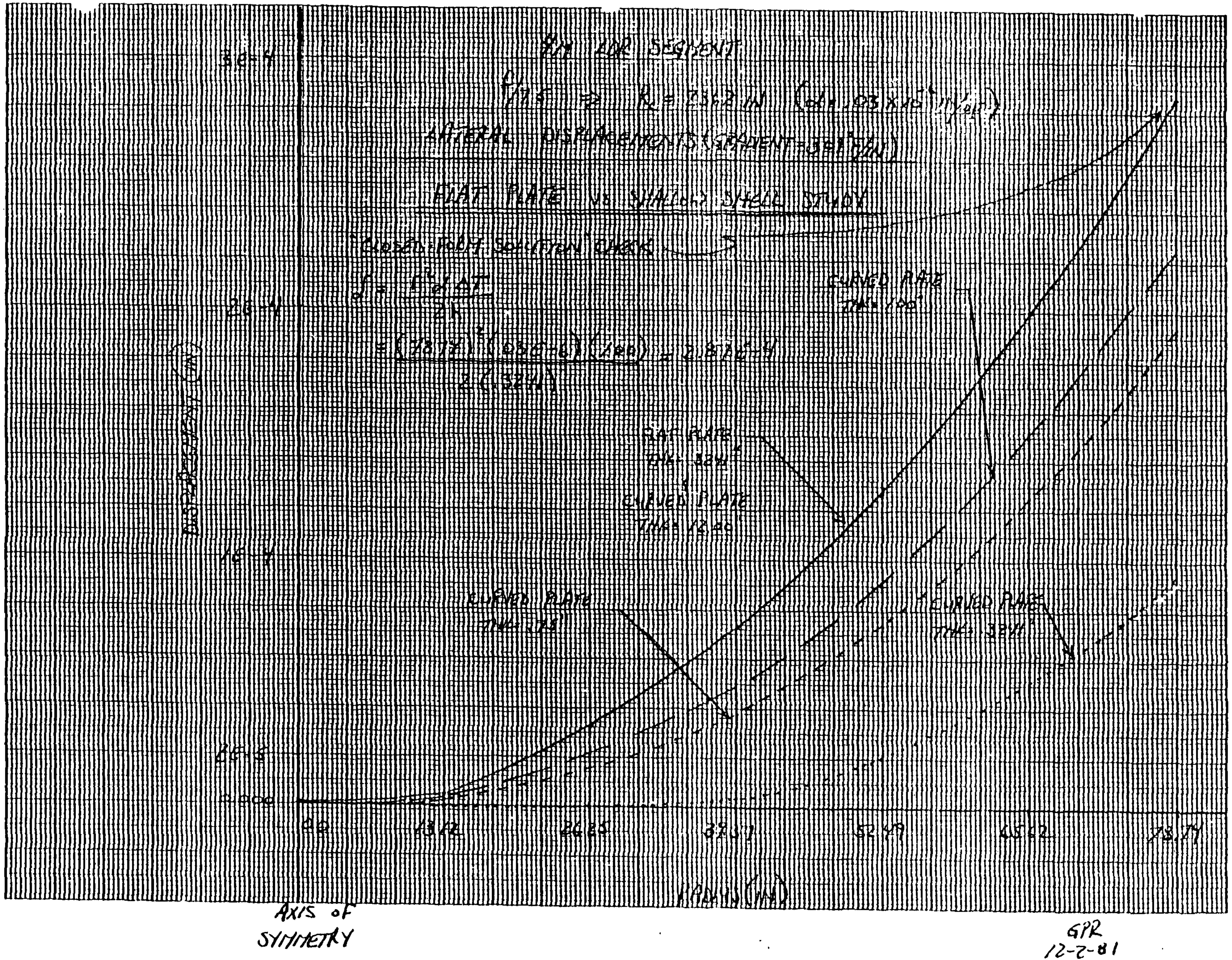
PANEL STUDIES

- 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

    (I.E.) $(\delta)_{PANEL} = \Delta T \times E \times \alpha \times (\delta)_{MODEL}$
- SEGMENT THICKNESS

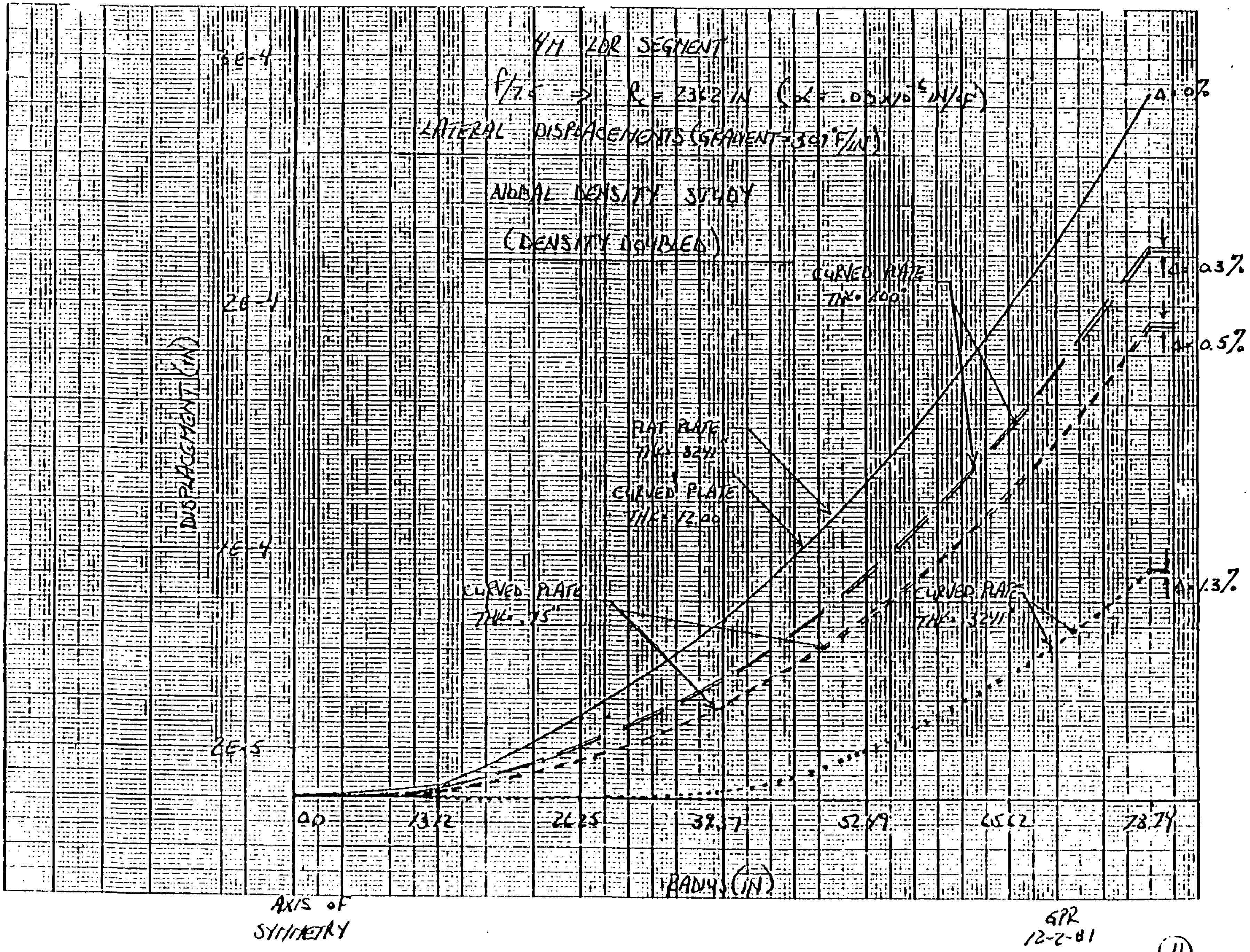
G.P.R. - 2/25/82

⑦


8 IN LDR SEGMENT
f/1.5 ⇒ R = 23.62 IN (α = .03 x 10⁻⁶ IN/IN°F)
LATERAL DISPLACEMENTS (GRADIENT = 38°F/IN)
FLAT PLATE vs SHALLOW SHELL STUDY
"CLOSED-FORM SOLUTION" CHECK
δ = r²αΔT / 2h
= (78.74)²(.03E-6)(400) / 2(.324) = 2.87E-4
3E-4
2E-4
1E-4
5E-5
0.000
DISPLACEMENT (IN)
0.0
13.12
26.25
39.37
52.49
65.62
78.74
RADIUS (IN)
CURVED PLATE THK=1.00
FLAT PLATE THK=.324
&
CURVED PLATE THK=12.40
CURVED PLATE THK=.25
CURVED PLATE THK=.324
AXIS OF SYMMETRY

GPR
12-2-81

(10)


4M LDR SEGMENT
f/7.5 ⇒ Rc = 2362 IN (α = .03×10⁻⁶ IN/°F)
LATERAL DISPLACEMENTS (GRADIENT = 3.01 °F/IN)
NODAL DENSITY STUDY
(DENSITY DOUBLED)
3E-4
2E-4
1E-4
2E-5
DISPLACEMENT (IN)
0.0
13.12
26.25
39.37
52.49
65.62
78.74
RADIUS (IN)
AXIS OF SYMMETRY
Δ: 0%
Δ: 0.3%
Δ: 0.5%
Δ: 1.3%
CURVED PLATE THK .200
FLAT PLATE THK .324
CURVED PLATE THK 12.00
CURVED PLATE THK .75
CURVED PLATE THK .324

GPR
12-2-81

⑪

BOUNDARY CONDITIONS

- A DESIGN CONSIDERATION (FOR RADIUS OF CURVATURE ADJUSTMENT):

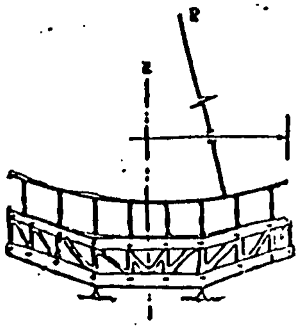
  POST SUPPORTED (IN THE LATERAL DIRECTION) INFINITE PLATES DO NOT BEND (EXCLUDING EDGE EFFECT PROPAGATION) DUE TO THRU-THE-THICKNESS THERMAL GRADIENT.

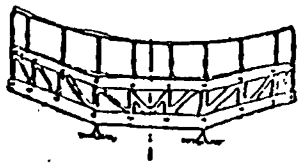
  - BOUNDARY CONDITIONS INVESTIGATED (2M & 4M SEGMENTS)

    1) STATICALLY DETERMINATE SYSTEM (RIGID BODY CONSTRAINTS)

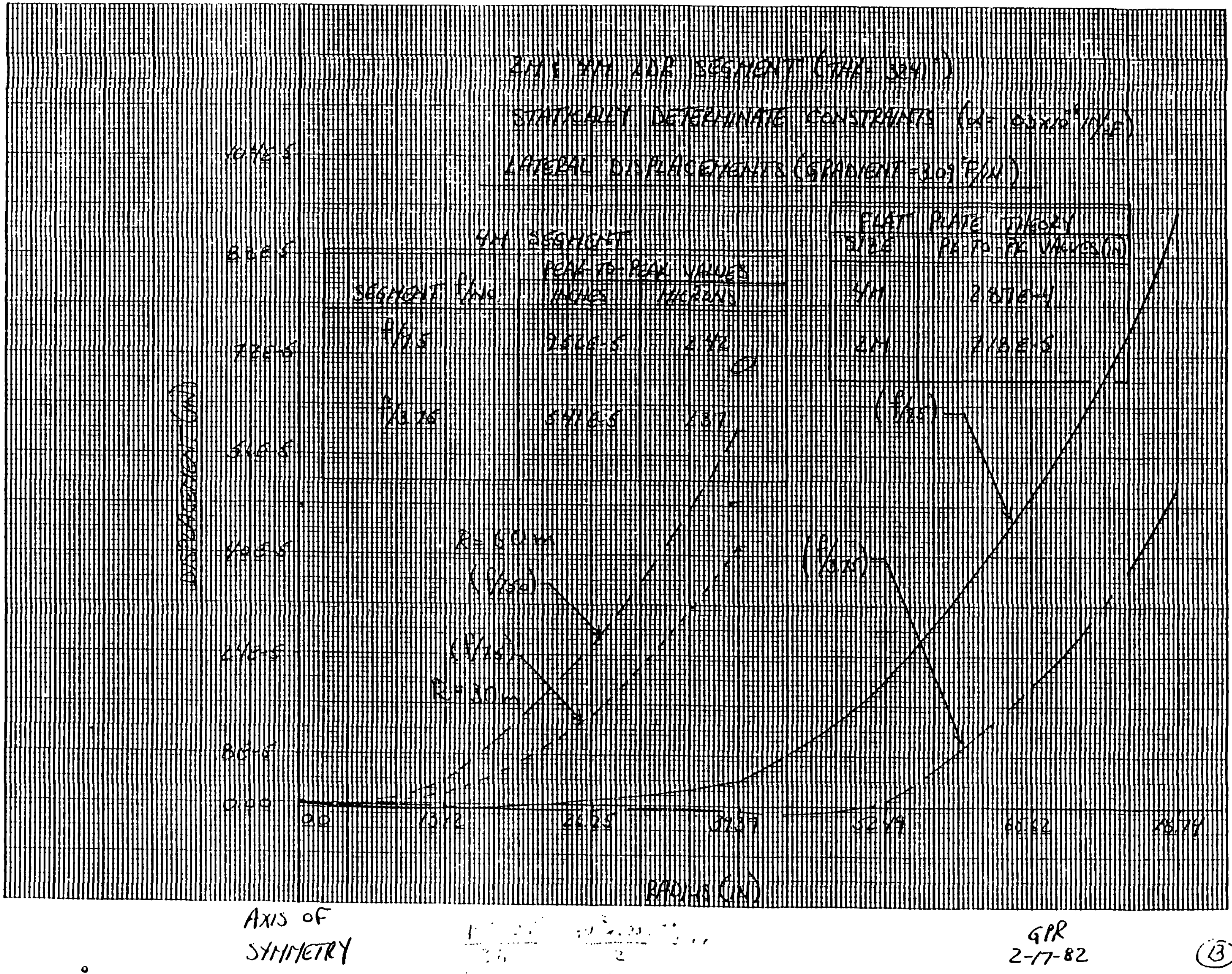
    2) POST SUPPORTED SEGMENT w/o EDGE SUPPORTS

    3) POST SUPPORTED SEGMENT WITH EDGE SUPPORTS





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



2M & 4M ADB SEGMENT (THK: 3/4")

STATICALLY DETERMINATE CONSTRAINTS ($\alpha = 0.3\times10^{-6}$ IN/IN/°F)

LATERAL DISPLACEMENTS (GRADIENT = 3.01 °F/M)

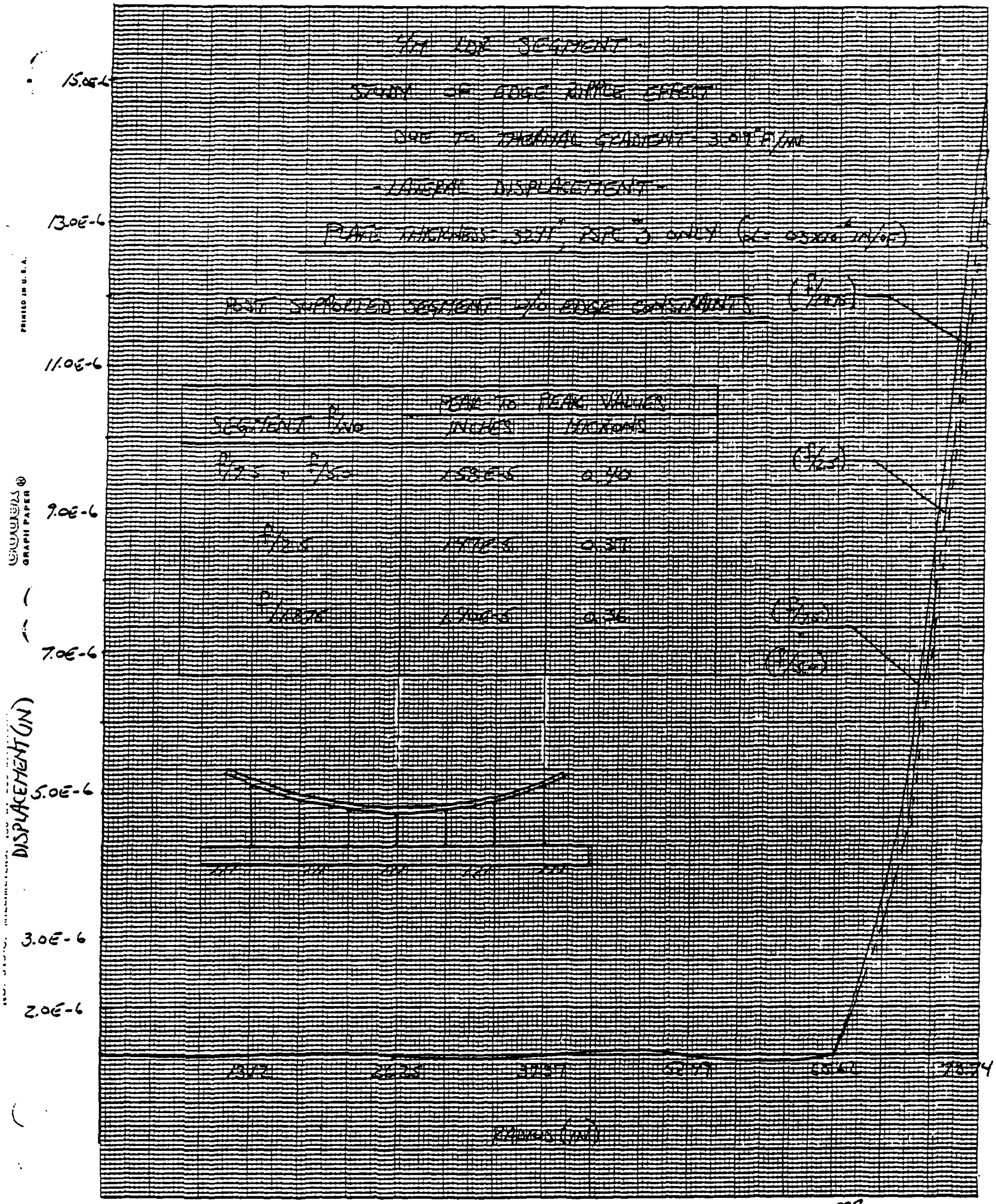
4M SEGMENT		
	PEAK-TO-PEAK VALUES	
SEGMENT P NO.	INCHES	MICRONS
P/7.5	9.56E-5	2.42
P/13.26	5.41E-5	1.37

FLAT PLATE THEORY	
SIZE	PK-TO-PK VALUES (IN)
4M	2.87E-4
2M	7.18E-5

GPR
2-17-82

⑬

ORIGINAL PAGE IS
OF POOR QUALITY



- 1/4 LDR SEGMENT -

STUDY OF EDGE RIPPLE EFFECT

DUE TO THERMAL GRADIENT - 3.0°F/IN

- LATERAL DISPLACEMENT -

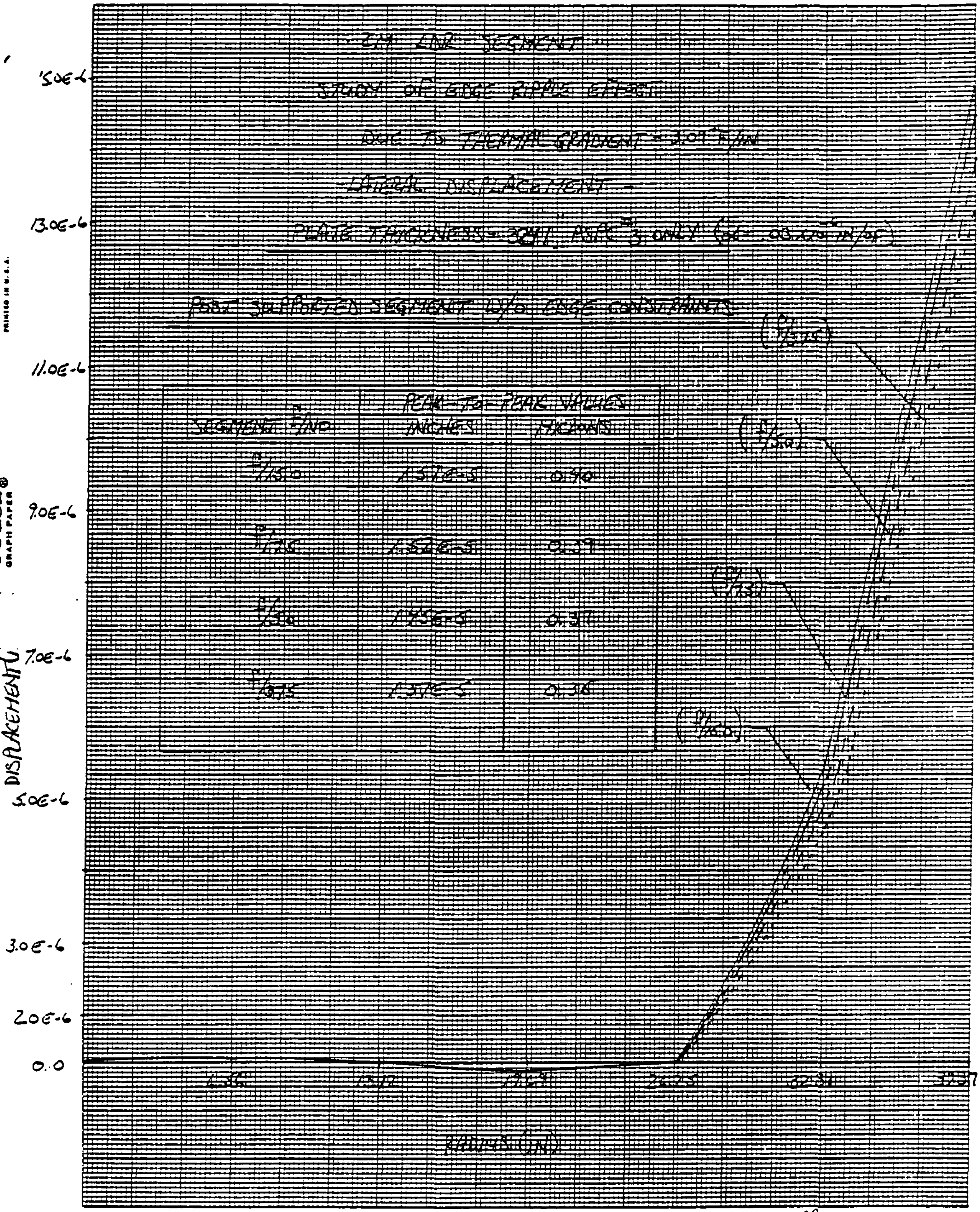
PLATE THICKNESS .3271", PSR 3 ONLY (α = .05x10⁻⁶ IN/IN°F)

POST SUPPORTED SEGMENT W/O EDGE CONSTRAINTS

SEGMENT f/NO	PEAK TO PEAK VALUES	
	INCHES	MICRONS
f/17.5 - f/50	1.58E-5	0.40
f/12.5	1.47E-5	0.37
f/1.875	1.40E-5	0.36

GPR
1-6-82

(14)



2M LDR SEGMENT

STUDY OF EDGE RIPPLE EFFECT

DUE TO THERMAL GRADIENT = 3.07 °F/IN

LATERAL DISPLACEMENT

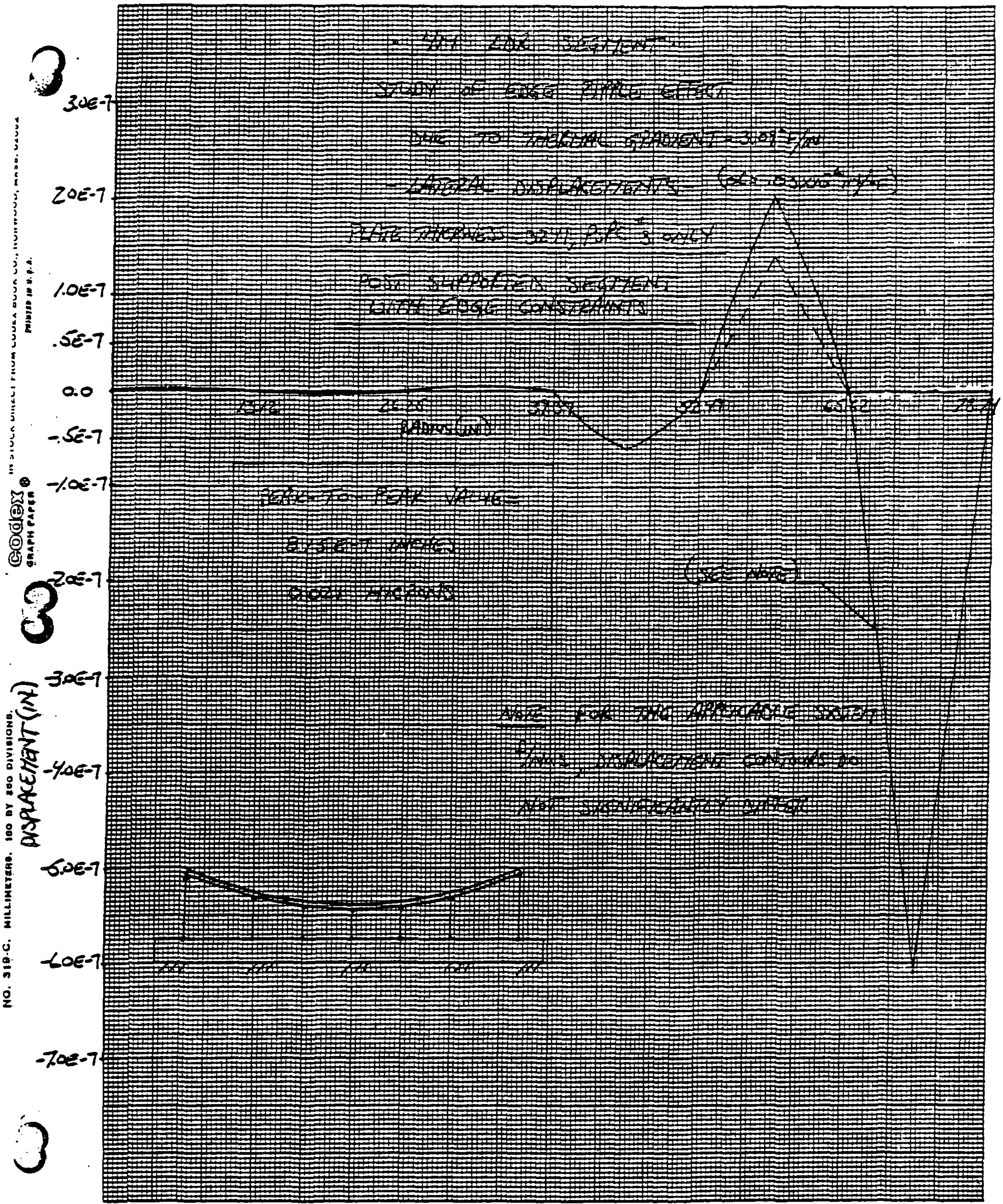
PLATE THICKNESS = .3041", ASPC 3 ONLY (α = .03×10⁻⁶ IN/°F)

POST SUPPORTED SEGMENT W/O EDGE CONSTRAINTS

SEGMENT P/NO	PEAK-TO-PEAK VALUES INCHES	 MICRONS
P/150	1.57E-5	0.40
P/75	1.52E-5	0.39
P/50	1.45E-5	0.37
P/37.5	1.37E-5	0.36

GPL
1-26-82

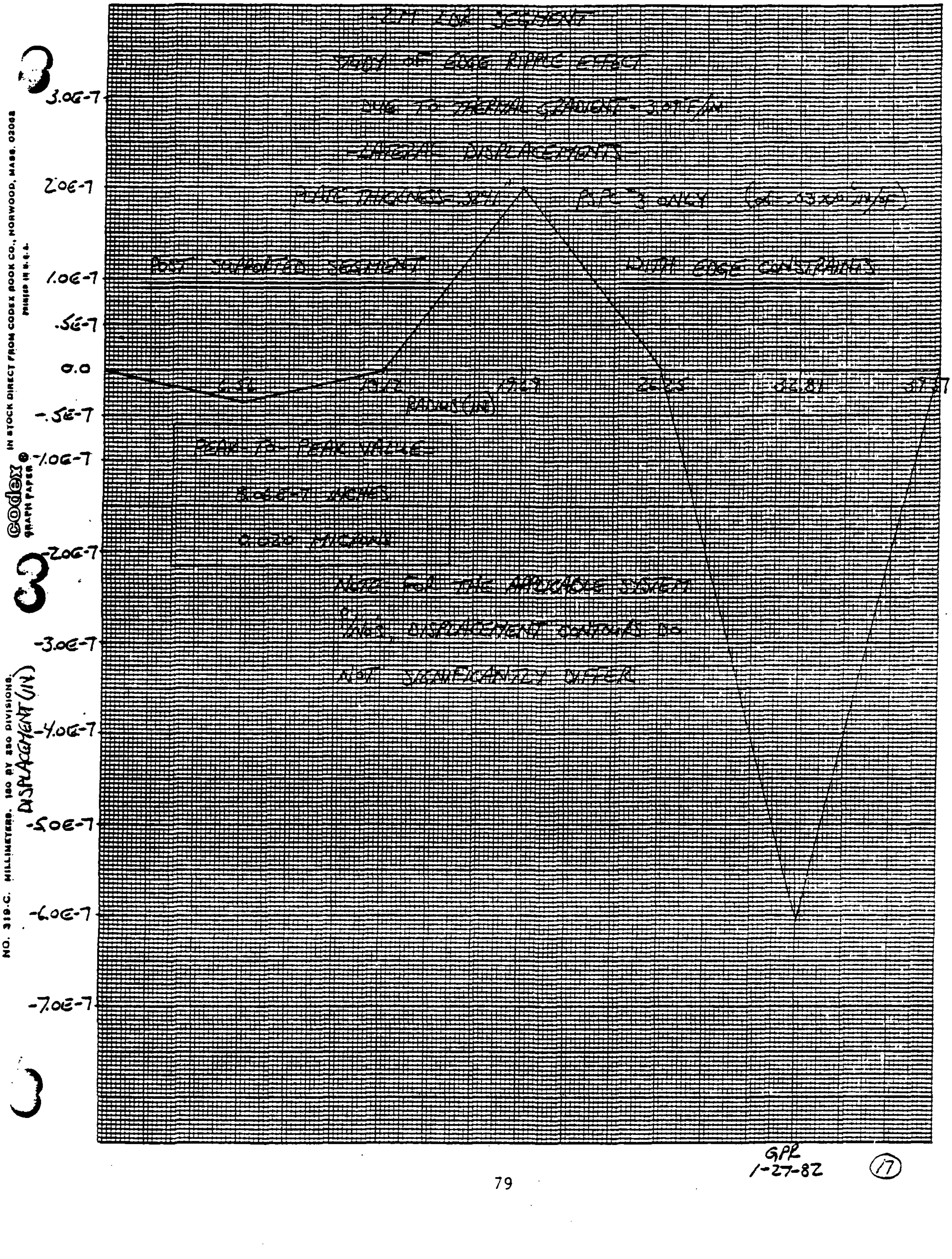
⑮


4M EDGE SEGMENT
STUDY OF EDGE RIPPLE EFFECT
DUE TO THERMAL GRADIENT = 3.0E-7 °F/IN
– LATERAL DISPLACEMENTS –
PLATE THICKNESS = .3211, P,R 3 ONLY
POINT SUPPORTED SEGMENT
WITH EDGE CONSTRAINTS
3.0E-7
2.0E-7
1.0E-7
.5E-7
0.0
-.5E-7
-1.0E-7
-2.0E-7
-3.0E-7
-4.0E-7
-5.0E-7
-6.0E-7
-7.0E-7
DISPLACEMENT (IN)
13.12
26.25
39.37
52.49
65.62
78.74
RADIUS (IN)
PEAK-TO-PEAK VALUE =
8.15E-7 INCHES
0.021 MICRONS
(SEE NOTE)
NOTE FOR THE APPLICABLE SEGMENT
SHAPES, DISPLACEMENT CONTOURS DO
NOT SIGNIFICANTLY DIFFER

GPL
1-6-82

⑯

ORIGINAL PAGE IS
OF POOR QUALITY



GPR
1-27-82

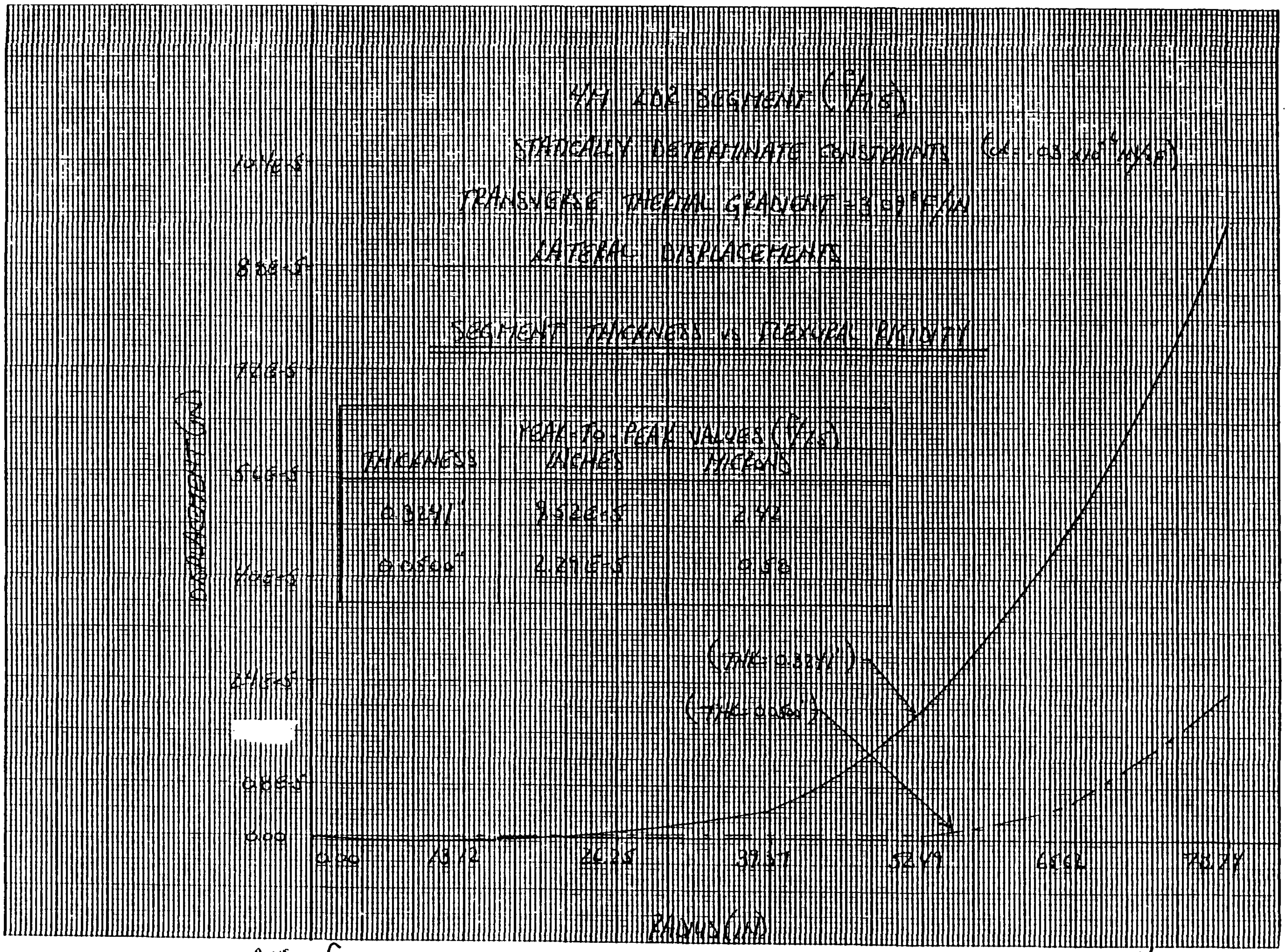
⑰

SEGMENT THICKNESS VARIATIONS

- SENSITIVTY OF THICKNESS ON STIFFNESS

⑱

ORIGINAL PAGE IS
OF POOR QUALITY



4/1 ADP SEGMENT (V/2S)

STATICALLY DETERMINATE CONSTRAINTS $(\alpha = .03 \times 10^{-4}$ IN/IN$)$

TRANSVERSE THERMAL GRADIENT = 3.09°F/IN

LATERAL DISPLACEMENTS

SEGMENT THICKNESS VS FLEXURAL RIGIDITY

THICKNESS	PEAK-TO-PEAK VALUES (V/2S) INCHES	MICRONS
0.3241"	9.52E-5	2.42
0.0500"	2.29E-5	0.58

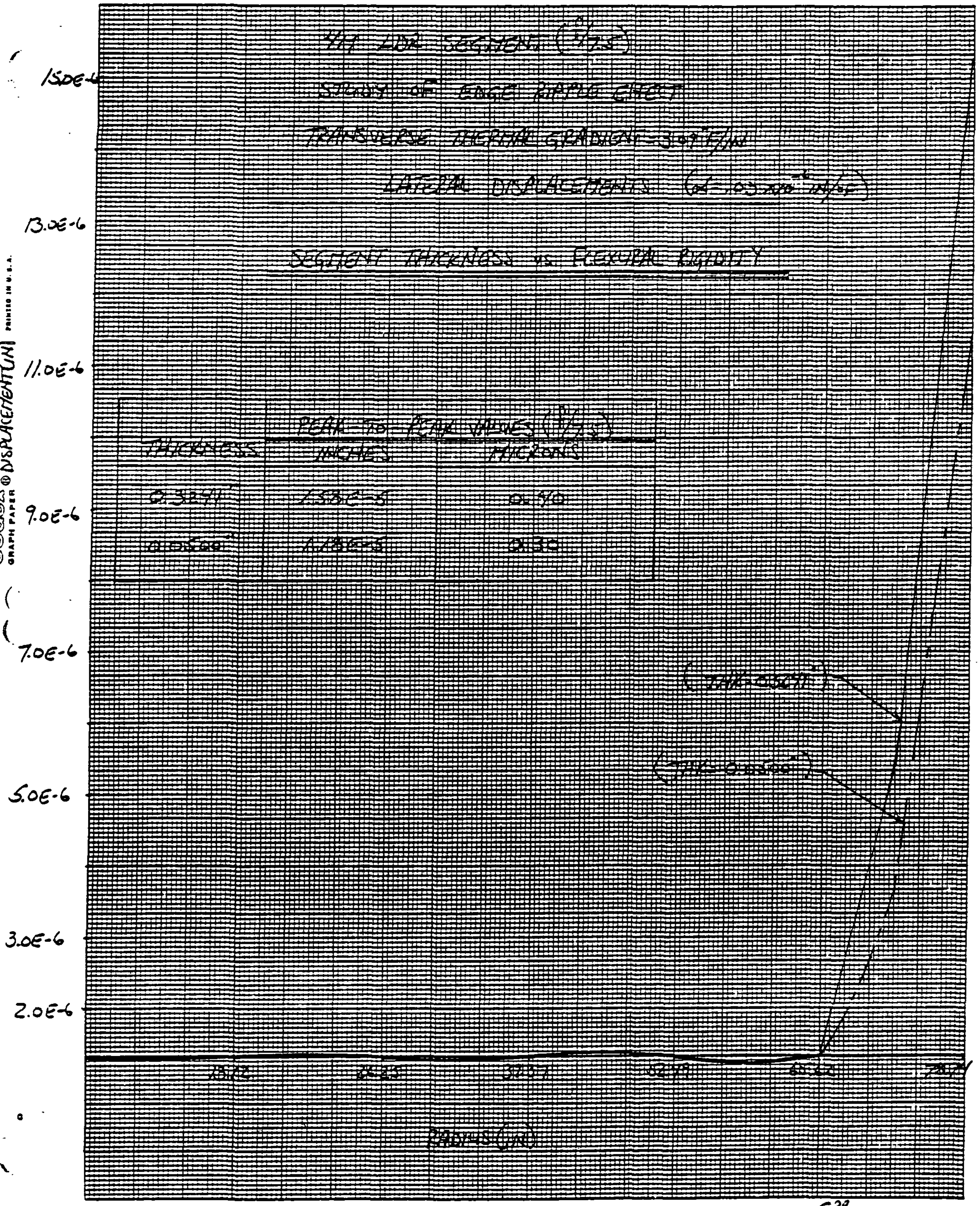
AXIS OF
SYMMETRY

GPR
2-8-82

(19)

81

ORIGINAL PAGE IS
OF POOR QUALITY



4/1 LDR SEGMENT (3/75)

STUDY OF EDGE RIPPLE EFFECT

TRANSVERSE THERMAL GRADIENT = 3.09°F/IN

LATERAL DISPLACEMENTS (α = .03×10⁻⁶ IN/°F)

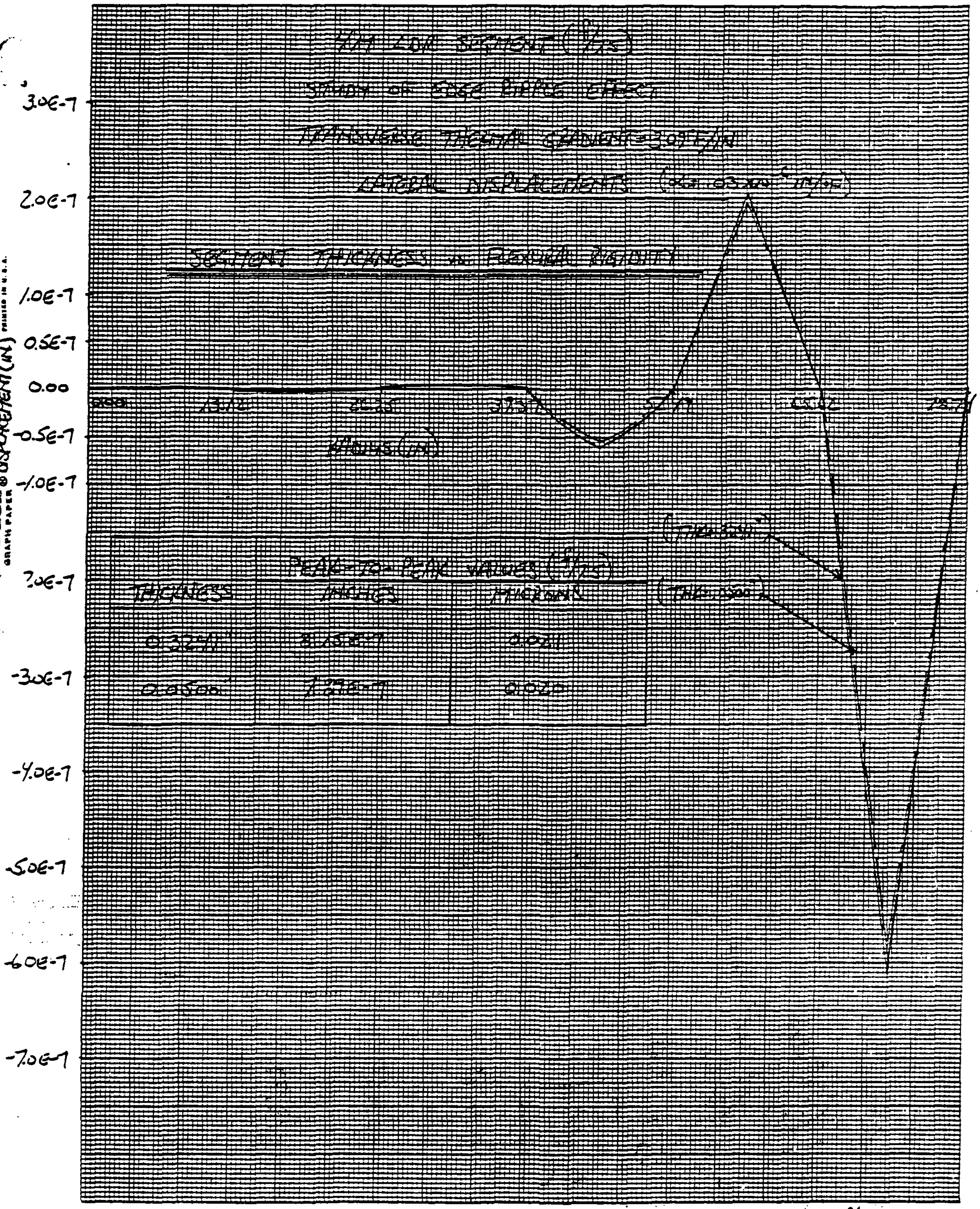
SEGMENT THICKNESS VS. FLEXURAL RIGIDITY

	PEAK-TO-PEAK VALUES (8/75)	
THICKNESS	INCHES	MICRONS
0.3241"	1.58E-5	0.40
0.0500"	1.18E-5	0.30

GPR
2-19-82

(25)

ORIGINAL PAGE IS
OF POOR QUALITY



PEAK-TO-PEAK VALUES (8/25)

THICKNESS	INCHES	MICRONS
0.3241"	8.15E-7	0.021
0.0500"	7.87E-7	0.020

GPR
2-17-82

$R = \frac{r^2}{2\Delta}$ $\Delta = \frac{r}{2R}$ $\therefore \Delta^2 = \frac{r^2}{4R^2}$

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

$\therefore dR = \frac{1}{2}\left(\frac{r}{\Delta}\right)^2 d\Delta$

$= \frac{1}{\cancel{2}} \frac{\cancel{r^2}\, 4R^2}{r^2} d\Delta$

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

ΔR CALCULATIONS

"FREE PLATE" → STATICALLY DETERMINATE
1.5M, 2M, & 4M LDR SEGMENT

$\Delta T = 3.09°F/IN$, $\alpha = .03 \times 10^{-6}$ IN/°F

$R_c = 2362$ IN (THK = .3241 IN)

NOTE: ALL DIMENSIONS IN INCHES

$\boxed{\frac{\Delta R}{R} = 2\frac{R}{r^2} d\Delta}$

$d\Delta_r$	INITIAL CURVATURE Y-COORDINATE (Δ_o)	DEFLECTION ($d\Delta$)	$\Delta R = \frac{-r^2}{2\Delta_o^2} d\Delta$	$\Delta R/R$
29.53	.1846 ✓	$4.04e^{-5}$ 1.~~25~~E-4 BAD? →	.12 -1.~~5994~~	.00022 .000677 ✓
39.37	.3279 ✓	5.96E-5 ✓	-0.4296	.000182
78.74	1.3128 ✓	9.487E-5 ✓	✓ -0.1706	✓.000072

$\Delta = \frac{r^2 \alpha \Delta T}{2h} = \frac{\cancel{900}\,1400 \times .03 \times 10^{-6}}{\cancel{2}} \times \cancel{3} = 4.04e^{-5}$

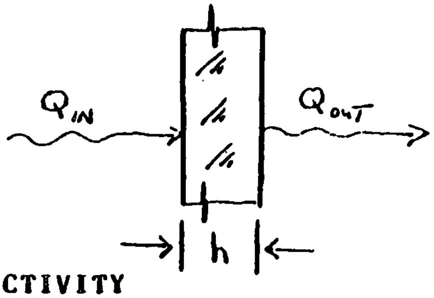
G.P.R. _ 2/25/82

TREND STUDY APPLICATION

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

(ΔT = 1.00°F FOR h = .3241")

- FOR STEADY STATE, $Q_{IN} = Q_{OUT}$



$$\frac{\Delta T}{h} = \frac{Q}{K}$$ K = THERMAL CONDUCTIVITY

$(Q)_{SYSTEM} \approx 0.011$ BTU/HR.IN^2 ✓

$(K)_{GLASS} \simeq 0.07$ BTU/HR.IN.°F

$(K)_{AL} \simeq 8.00$ BTU/HR.IN.°F

$$\therefore \left(\frac{\Delta T}{H}\right)_{GLASS} = \frac{0.011}{0.07} = 0.16\ °F/IN \rightarrow \frac{3.09°F/IN}{0.16°F/IN} = 19.31$$

$$\left(\frac{\Delta T}{H}\right)_{AL} = \frac{0.011}{8.00} = 0.0014\ °F/IN \rightarrow \frac{3.09°F/IN}{0.0014\ °F/IN} = 2207.14$$

} REDUCTION FACTORS TO BE APPLIED TO SENSITIVITY DISPLACEMENT DATA

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

㉓

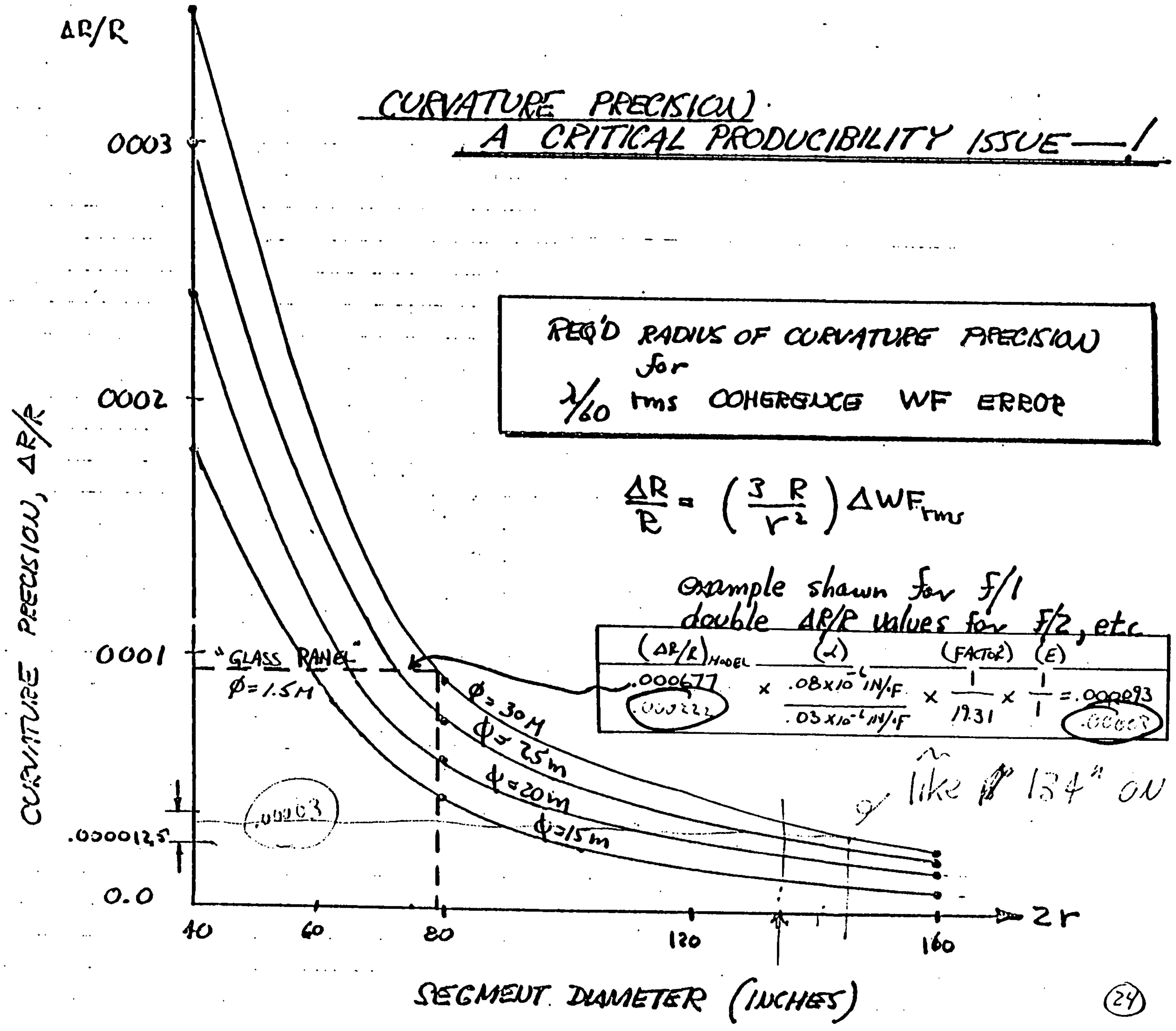
CURVATURE PRECISION
A CRITICAL PRODUCIBILITY ISSUE—!

REQ'D RADIUS OF CURVATURE PRECISION
for
λ/60 rms COHERENCE WF ERROR

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

example shown for f/1
double ΔR/R values for f/2, etc

$$\overset{(\Delta R/R)_{MODEL}}{\underset{.000222}{.000677}} \times \overset{(\alpha)}{\frac{.08\times10^{-6}\,\text{IN/°F}}{.03\times10^{-6}\,\text{IN/°F}}} \times \overset{(\text{FACTOR})}{\frac{1}{19.31}} \times \overset{(E)}{\frac{1}{1}} = \underset{.00003}{.000093}$$



like 134" ON PG. 19

CONCLUSIONS

- MODELS WORKING PROPERTY AND READY FOR DETAILED STUDY OF SELECTED CANDIDATES.
- SHELL CHARACTERISTICS SHOW STIFFENING EFFECT
  - MAKES FLAT PLATE EVALUATION CRITERIA RESULTS CONSERVATIVE
- $\Delta R/R$ THERMAL EFFECT WITHIN SPEC. FOR THIN "GLASS" SHELLS

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

(25)

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

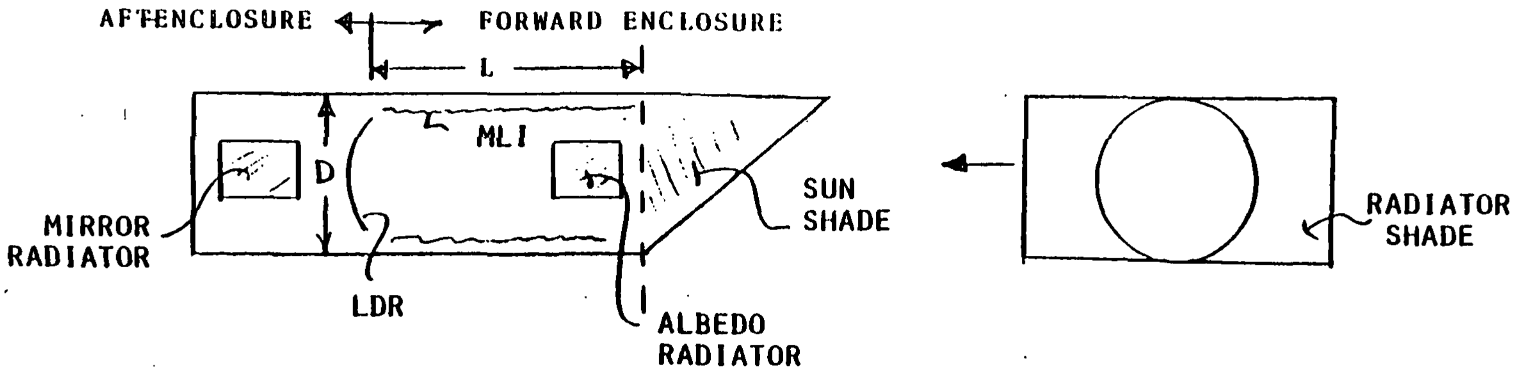
①

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

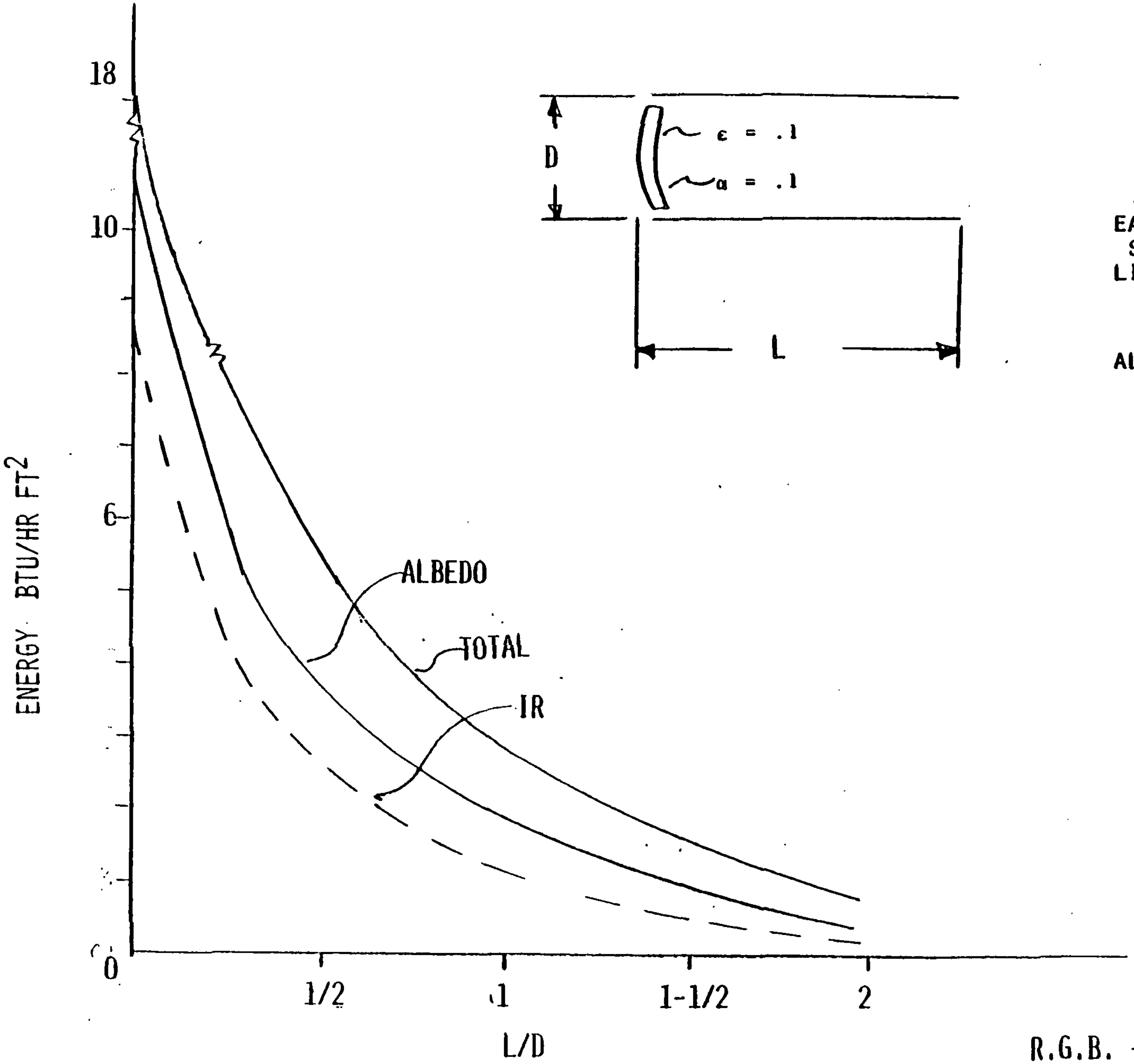
LDR ENCLOSURE DESIGN PARAMETERS

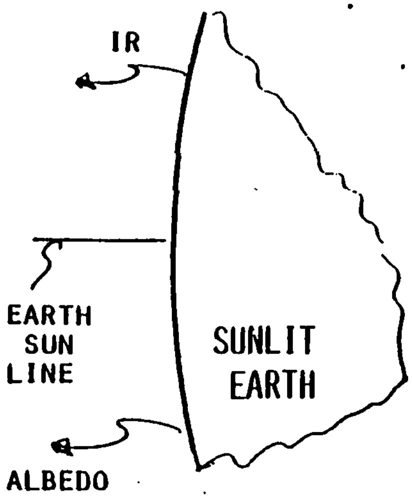


PARAMETER	
FWD ENCLOSURE LENGTH (L)	CONTROLS ENERGY IRRADIATING/ABSORBED BY LDR
ENCLOSURE MLI	MINIMIZES SIDE TO SIDE GRADIENTS WITH MLI MAX = .40°F WITHOUT MAX = 460°F
RADIATOR RADIATOR/SHADE	PROVIDES AN AREA FOR EARTH IR AND ALBEDO ENERGY REJECTION
SUN SHADE	ELIMINATES POSSIBILITY OF THE SUN IRRADIATING THE INTERIOR OF THE FORWARD ENCLOSURE.
MATERIAL ABSORBTIVITY (α) EMISSIVITY (ϵ)	THERMAL RADIATION PARAMETERS TYPICAL VALUES EXTERNAL ENCLOSURE $\alpha/\epsilon = .2/.8$ LDR $\alpha/\epsilon = .1/.1$, INTERNAL ENCLOSURE $\alpha/\epsilon = .8/.8$

(3)

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

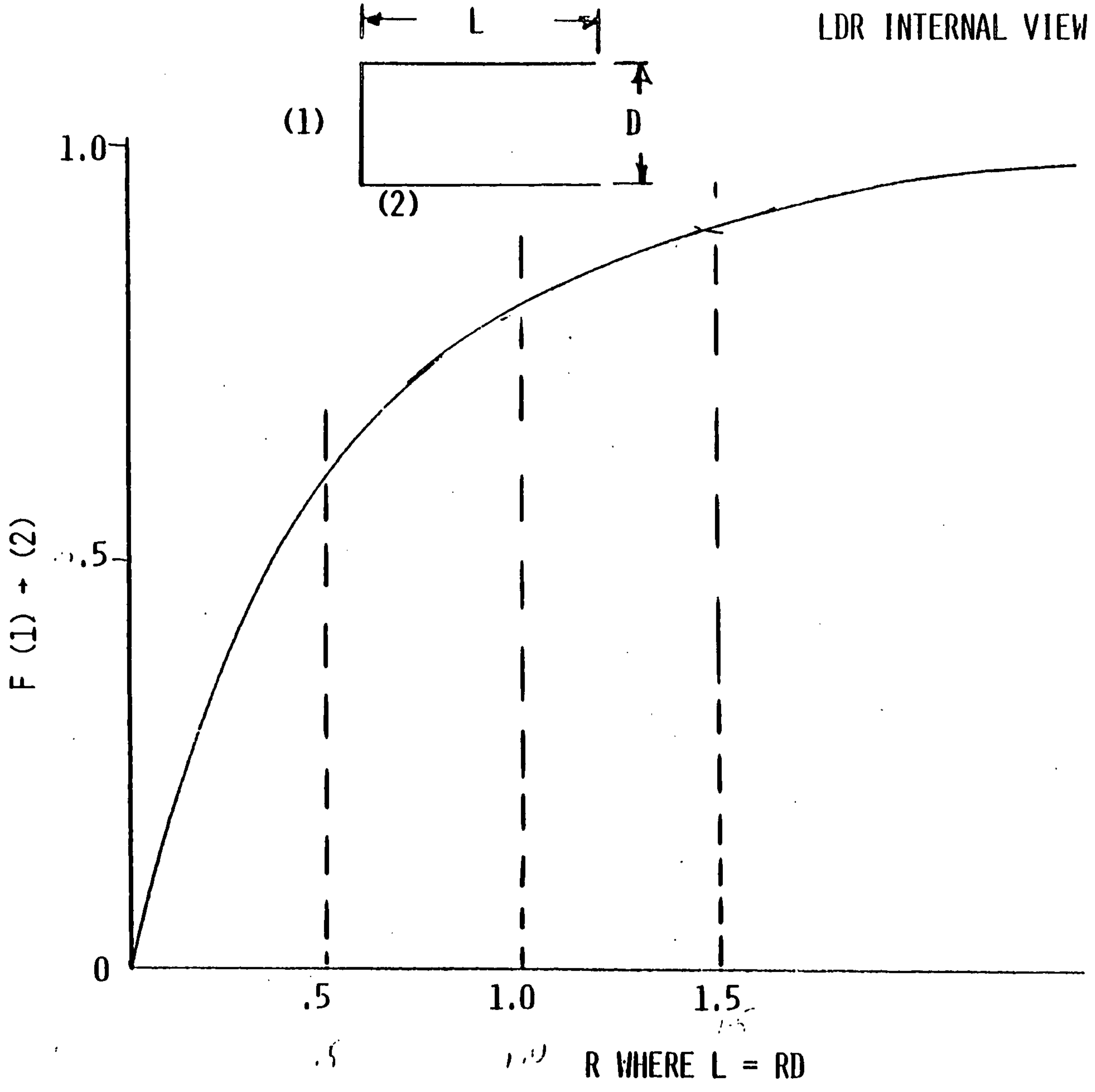
EARTH ALBEDO 192 BTU/HR FT^2

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

4-3

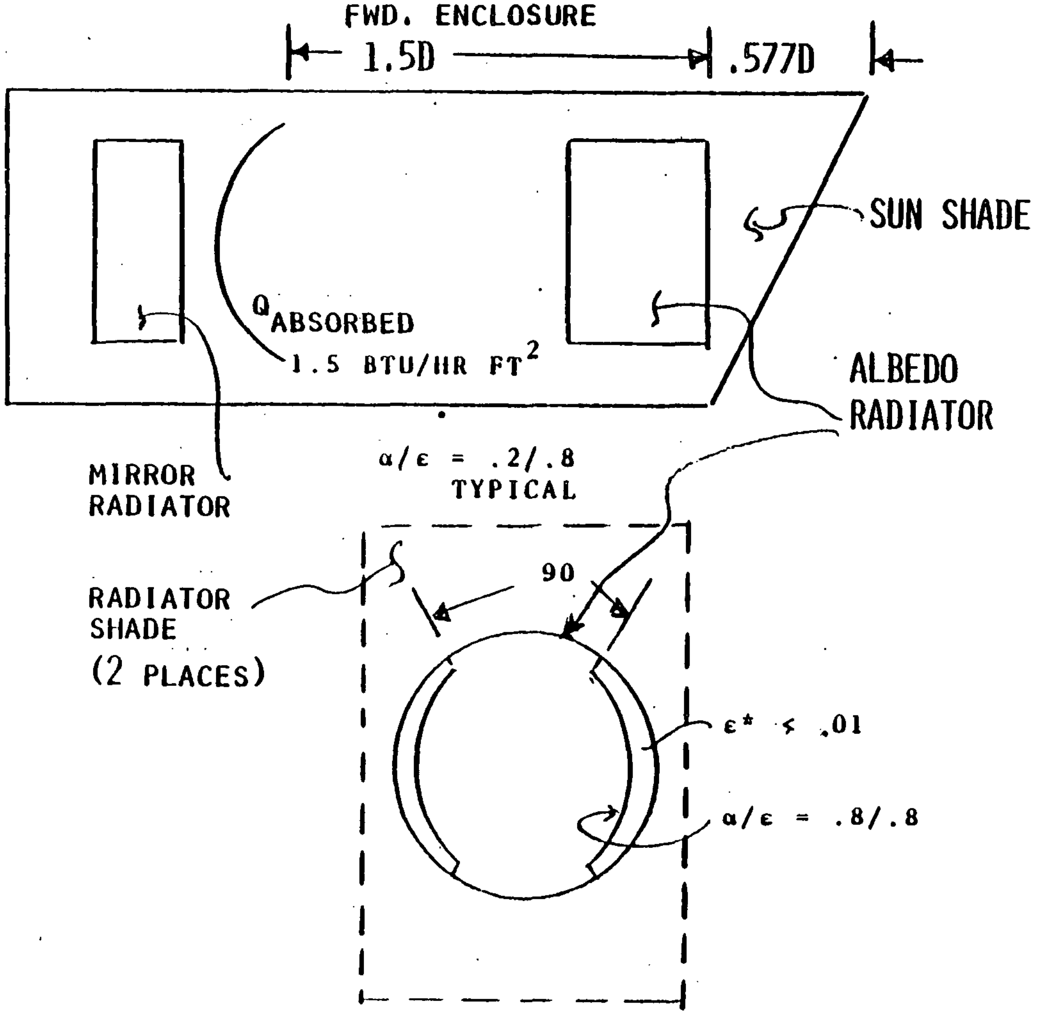
⑦

LDR INTERNAL VIEW TO SPACECRAFT



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

5



TEMPERATURE

T_{MAX} ~ -105°F (197°K)

T_{AVE} ~ -120°F (188°K)

T_{MIN} ~ -127°F (185°K)

SIDE TO SIDE ABSORBED ENERGY VARIATION $< \pm$ ~~.15~~ .20 BTU/HR FT^2

SIDE TO SIDE TEMPERATURE VARIATION <.40°F

LDR THERMAL ENCLOSURE

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

4-4

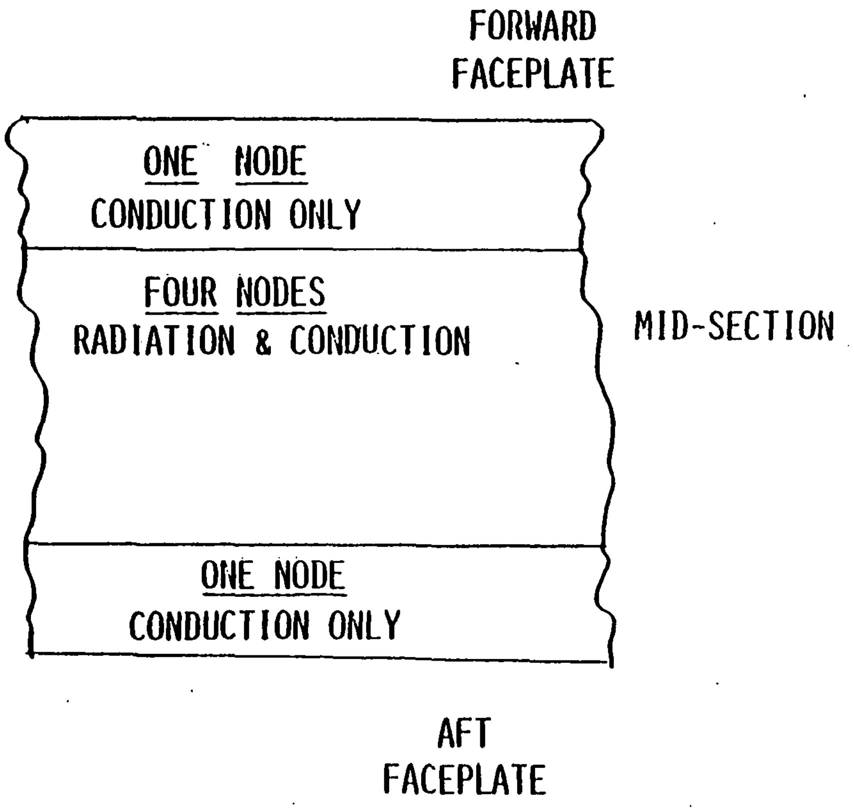
⑥

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 NASTRAN COMPATIBLE



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

⑦

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

APPENDIX C

FINAL BRIEFING

LDR

SEGMENT TECHNOLOGY ASSESSMENT

FINAL BRIEFING

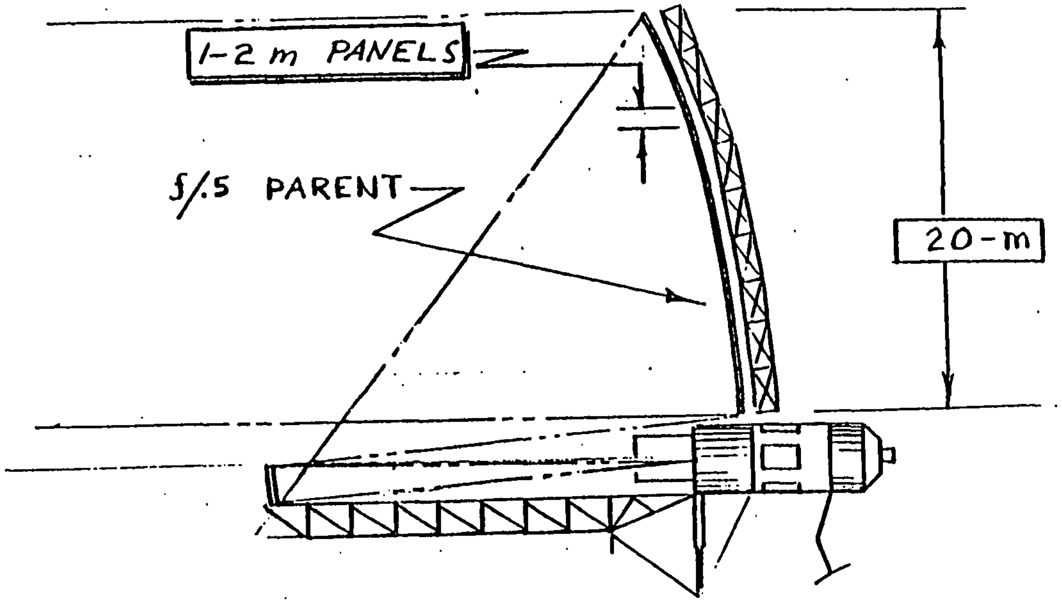
9/21/82

PERKIN- ELMER

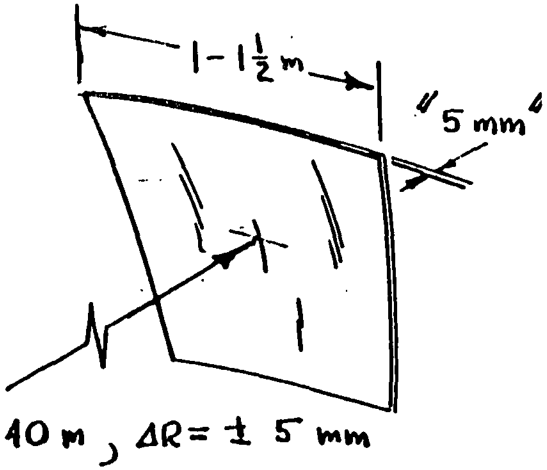
LDR

LARGE DEPLOYABLE REFLECTOR

SPONSOR : NASA-AMES



- IR APPLICATIONS @ $2 < \lambda < 30\ \mu m$
- ULTRA LIGHTWEIGHT : 10-15 Kg/m^2
- PASSIVE (PANEL) STABILITY @ 200 °K
- "AFFORDABLE"
- 1987 TECHNOLOGY READINESS



TYPICAL PANEL

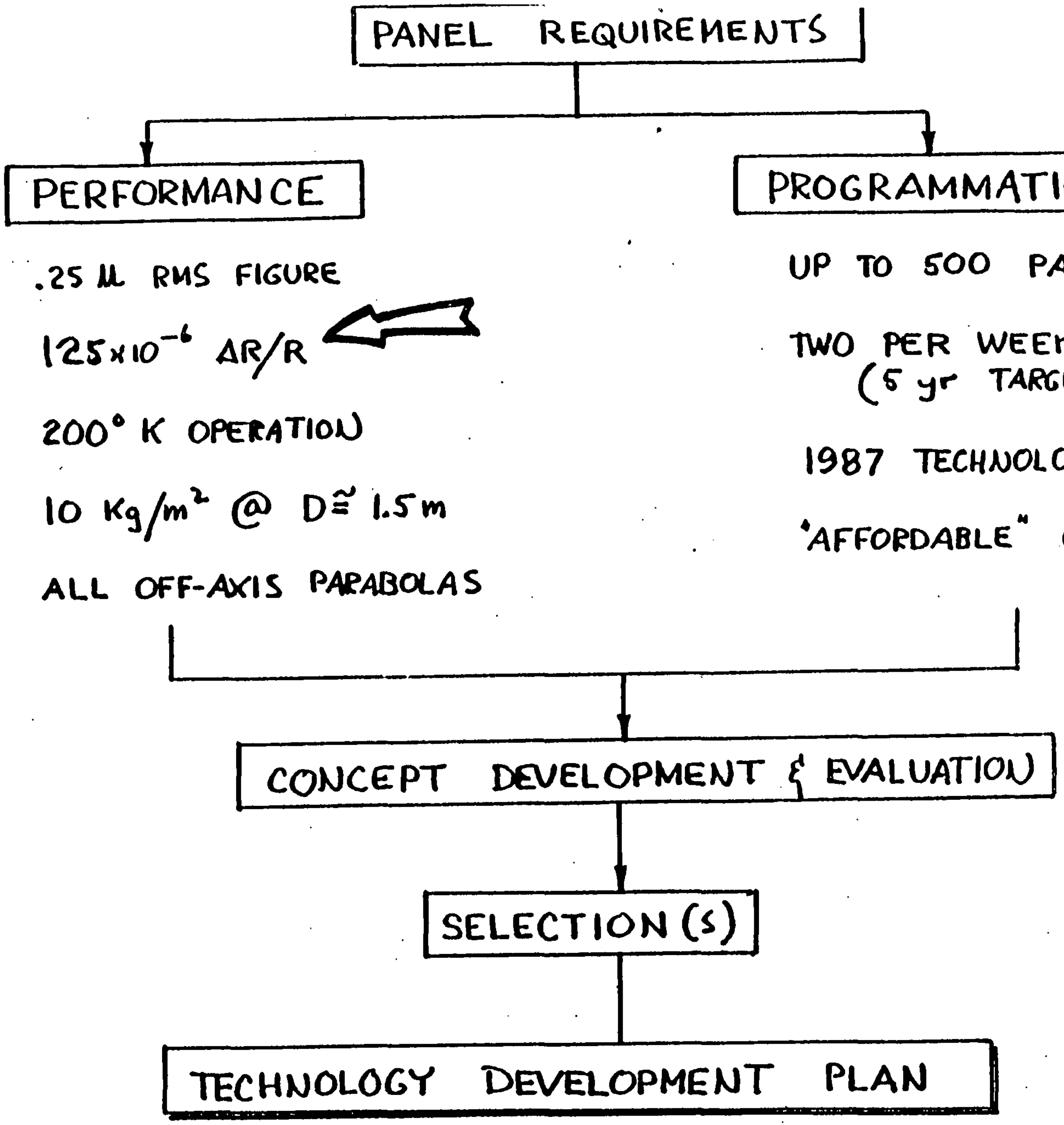
TOP LEVEL LDR REQUIREMENTS

(FROM SOW & ATTACHMENTS)

20 m

OVERALL DIA	$10 \leq D \leq 30$ M
FIGURE TYPE	PARABOLA OR HYPERBOLA/NOT SIMPLY SPHERICAL
FIGURE QUALITY	D/L @ $30\,\mu \rightarrow \frac{\lambda}{13.7}$ RMS OR $\left.2.2\,\mu\right]_{\text{SYSTEM}} \longrightarrow 2\,\mu_{\text{RMS}}$ MIRROR
SPEED	F/.5 TO F/1
WEIGHT	25000 LBS (11360KG) INCL ACTUATORS
OPERATING TEMP	150 - 200°K (-100 TO -190°F)
OPERATING W/L	$2\,\mu$ TO $1000\,\mu$
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 ~ outgassing / dimensional change

10/15/81 MK



PANEL REQUIREMENTS

PERFORMANCE

- .25 μ RMS FIGURE
- 125×10^{-6} ΔR/R
- 200° K OPERATION
- 10 Kg/m^2 @ D≅ 1.5 m
- ALL OFF-AXIS PARABOLAS

PROGRAMMATICS

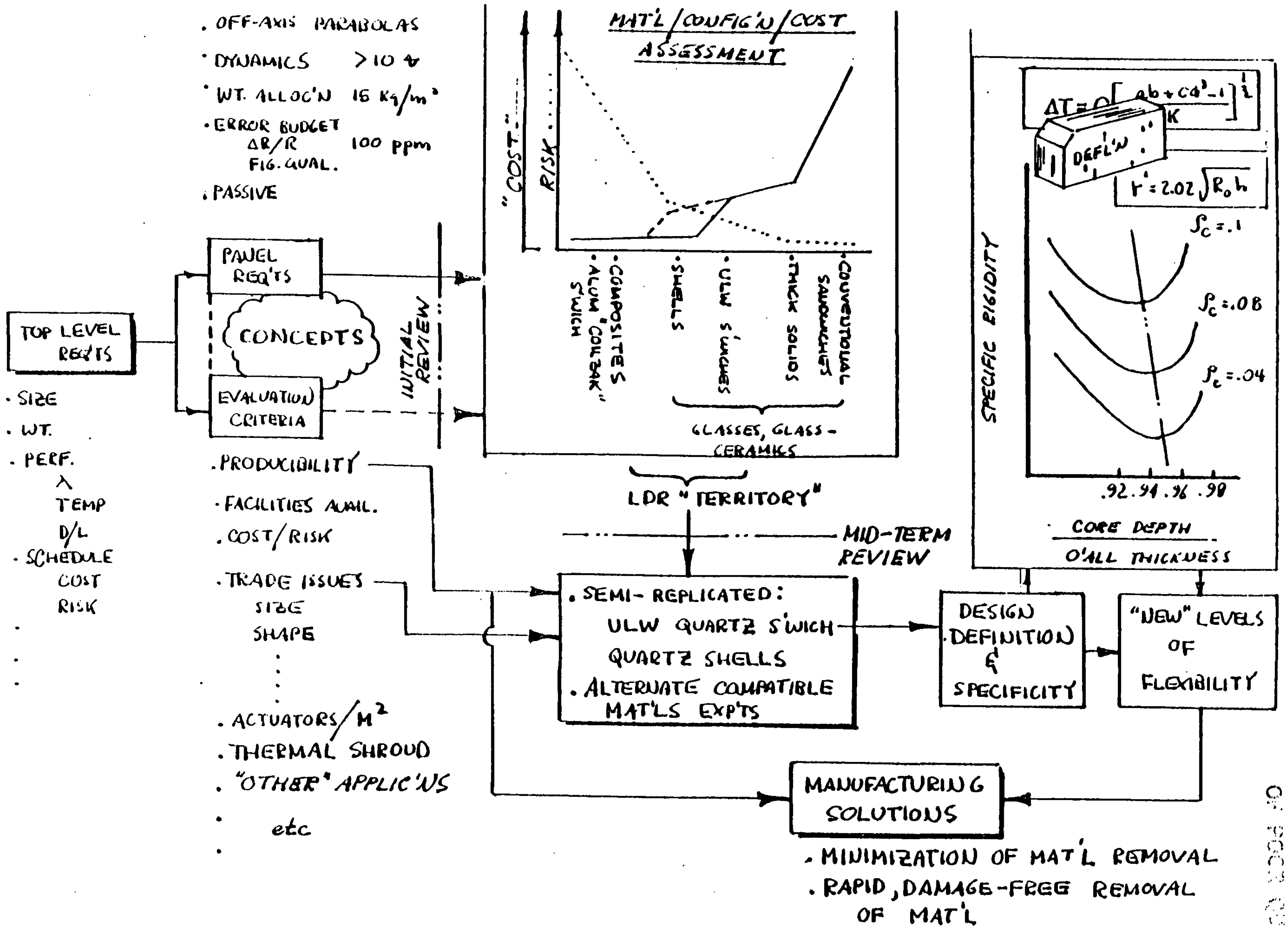
- UP TO 500 PANELS REQ'D
- TWO PER WEEK SCHEDULE GOAL (5 yr TARGET)
- 1987 TECHNOLOGY READINESS
- "AFFORDABLE" COSTS

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/m^2 1.5 - 2 m DIAMETER
  - SEMI-REPLICATION
  - UNIQUE MANUFACTURING IDEAS
- ALTERNATE MATERIAL EXPERIMENTS
  - ADDITIONAL (DOMESTIC) SOURCE

REQUIREMENTS AND EVALUATION CRITERIA

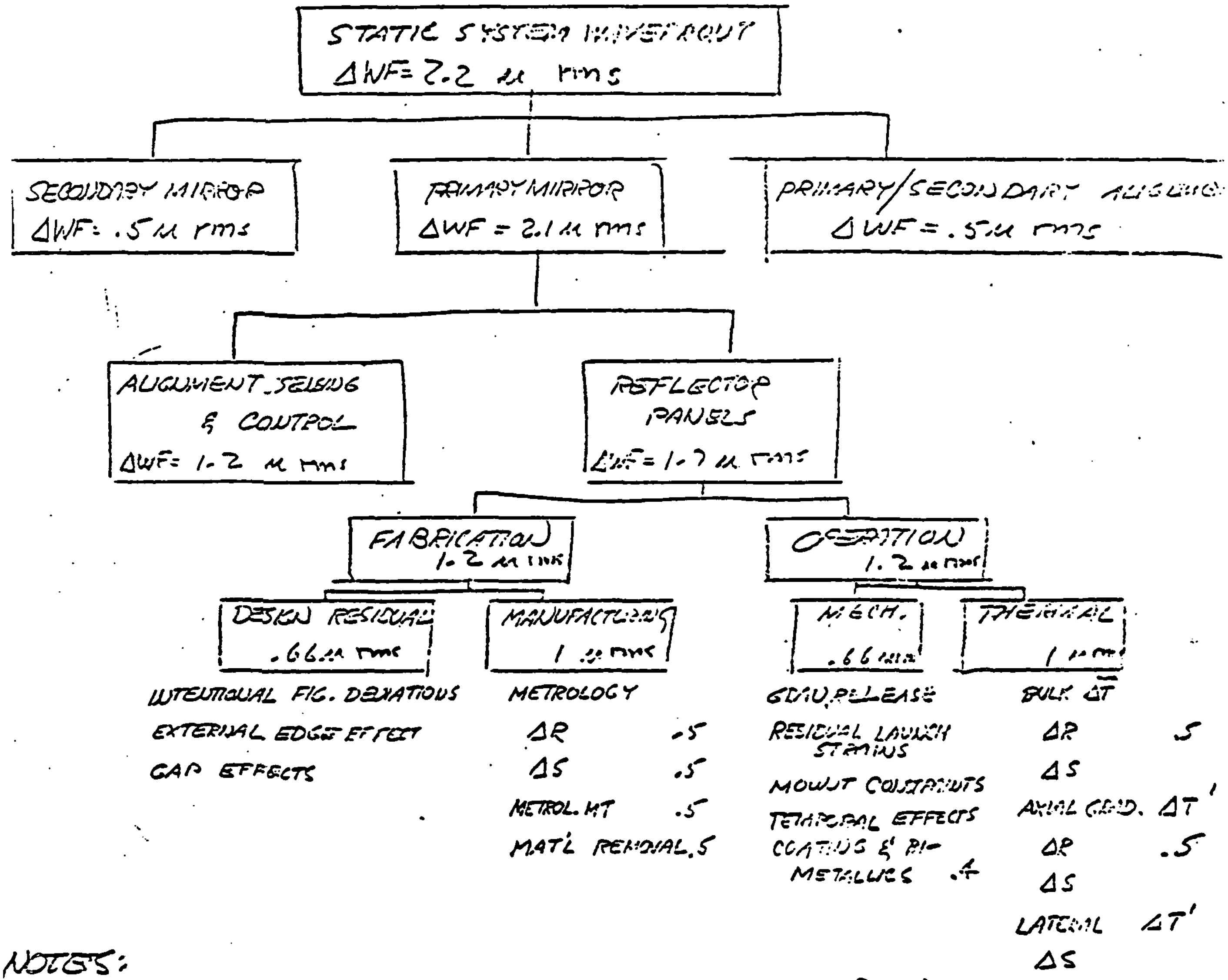
REQUIREMENTS & EVALUATION CRITERIA

- $\Delta R/R$ or RADIUS OF CURVATURE PRECISION
  - ABSOLUTE SURFACE ACCURACY A KEY ISSUE FOR COHERENT SEGMENTED PERFORMANCE
  - CONCLUDED THAT $1\frac{1}{2}$ 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 μm = $\frac{30}{13.7}$ = 2.2 μ rms



NOTES:

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

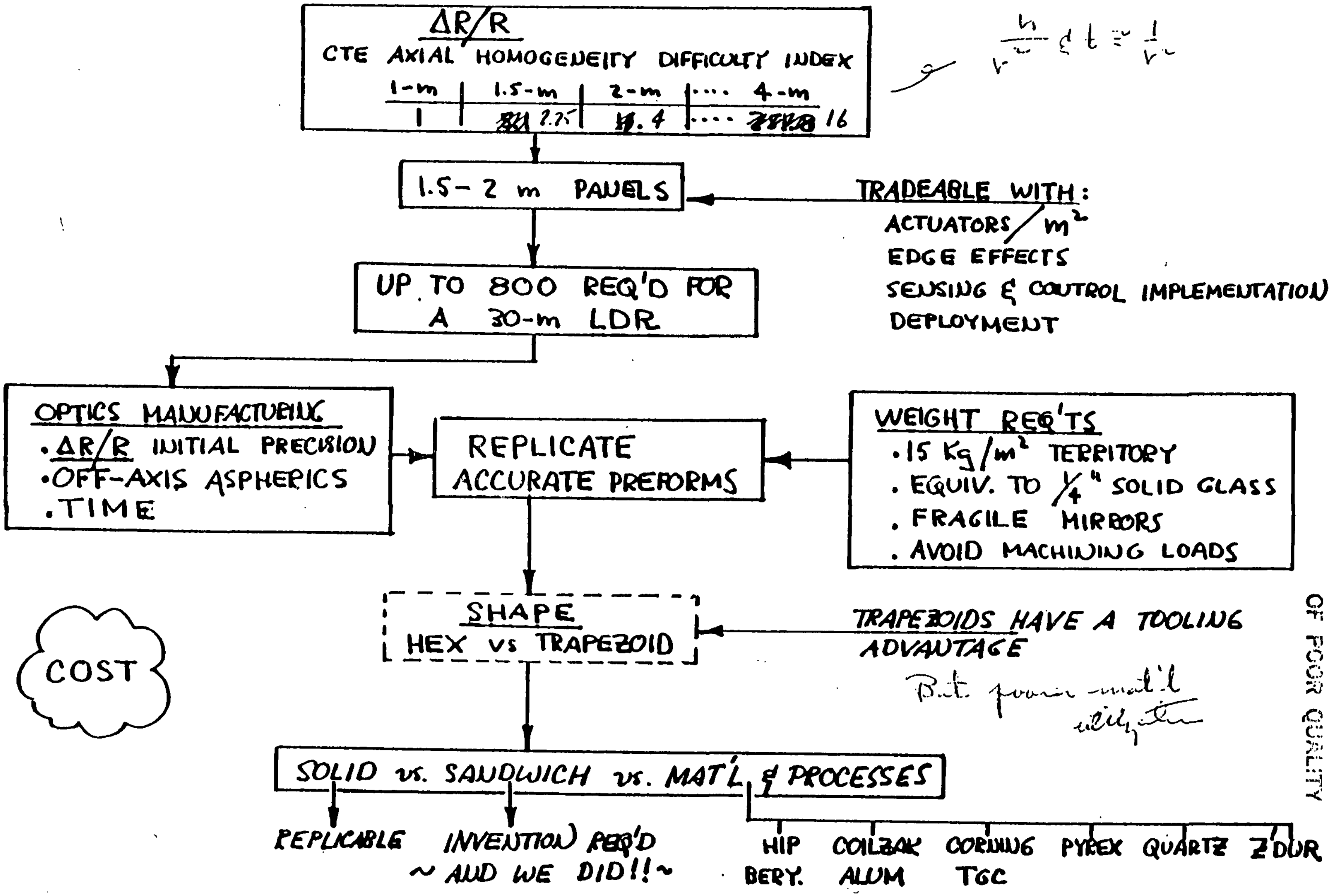
2. TOTAL RSS ΔR WAVEFRONT ERROR = .95 μ rms
   MFG " " " " = .5
   OP'N " " " " = .81

From Tech Doc

THE ΔR/R INFLUEN~~CE~~ TREE

$w = \pi r^2 \rho t$ $\therefore \frac{1}{r^2}$

$\frac{h}{r^2}$ & $t \cong \frac{1}{r^2}$



ΔR/R
CTE AXIAL HOMOGENEITY DIFFICULTY INDEX

1-m	1.5-m	2-m	.... 4-m
1	~~[illegible]~~ 2.25	4	.... ~~[illegible]~~ 16

1.5-2 m PANELS

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

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

TRAPEZOIDS HAVE A TOOLING ADVANTAGE

But poorer mat'l utilization

COST

SOLID vs. SANDWICH vs. MAT'L & PROCESSES

REPLICABLE

INVENTION REQ'D
~ AND WE DID!! ~

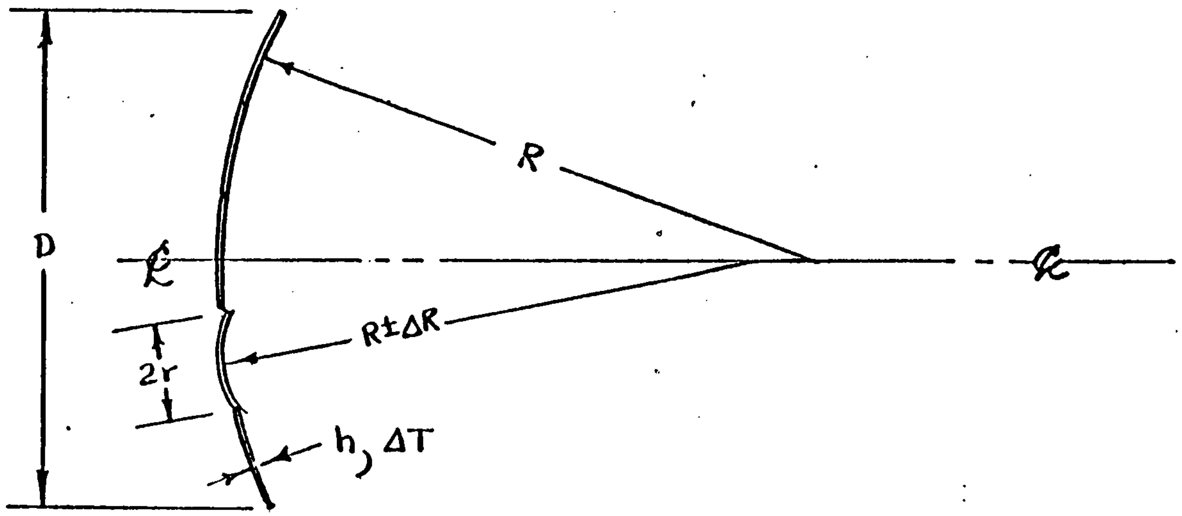
HIP BERY.
COILBAK ALUM
CORNING TGC
PYREX
QUARTZ
Z'DUR

CURVATURE PRECISION

- UNIQUE TO COHERENT SEGMENTED MIRRORS.
- AN INITIAL MANUFACTURING AND....
- MATERIAL SELECTION ISSUE.

RADIUS OF CURVATURE PRECISION

BIG DRIVER FOR PHASED (COHERENT) OPERATION

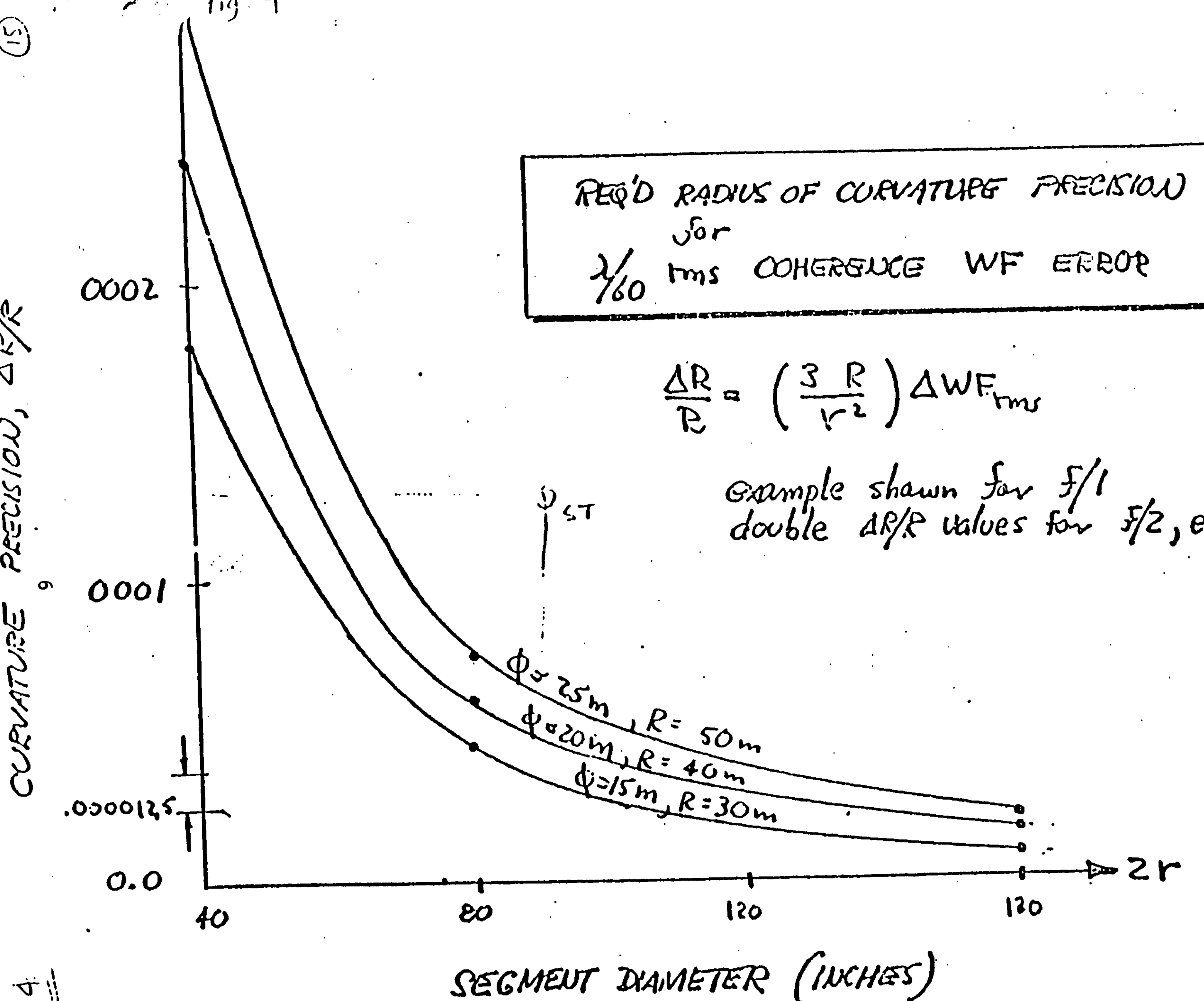


$$\Delta WF \cong \frac{1}{3}\left(\frac{r}{R}\right)^2 \Delta R \qquad \& \quad \Delta R = \frac{R^2 \alpha \Delta T}{h}$$

$$\Delta WF = \frac{1}{3} r^2 \alpha \frac{\Delta T}{h}$$

FAVORS SMALL PANELS

Fig 4



REQ'D RADIUS OF CURVATURE PRECISION for $\lambda/60$ rms COHERENCE WF ERROR

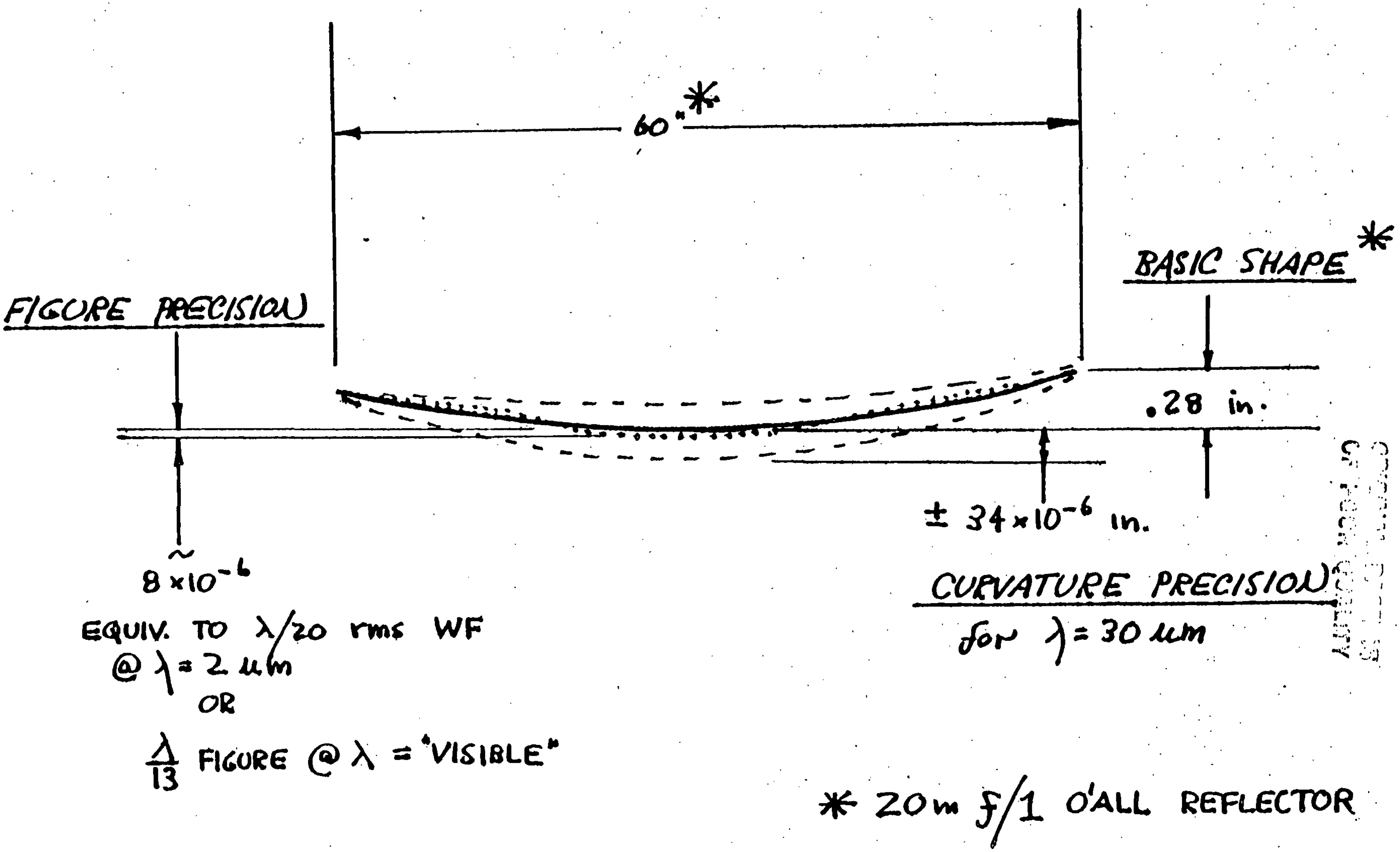
$$\frac{\Delta R}{R} = \left(\frac{3\ R}{r^2}\right)\Delta WF_{rms}$$

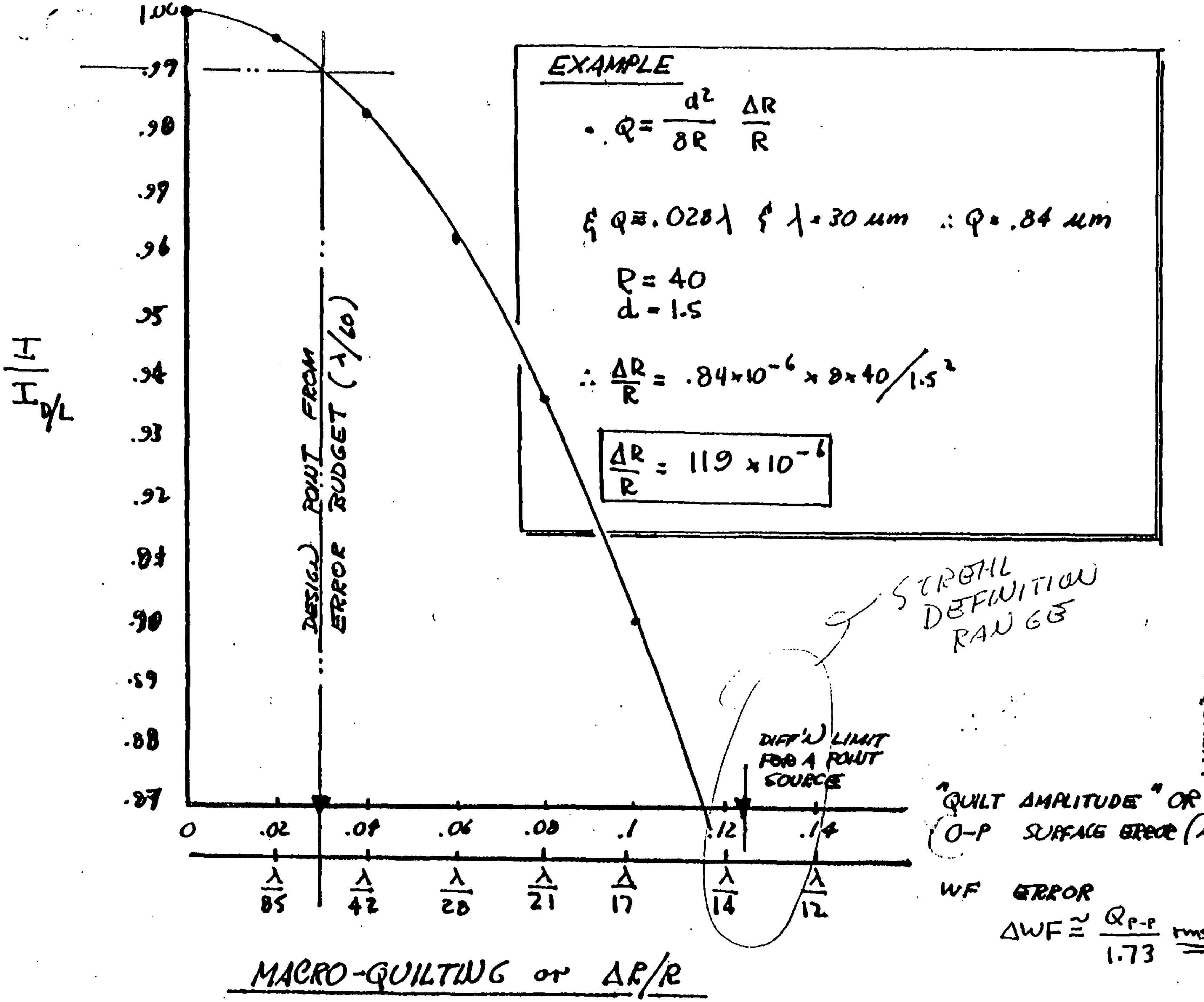
Example shown for f/1
double ΔR/R values for f/2, etc

FIG. 4

Fig. 4

ABSOLUTE SURFACE PRECISION REQ'TS for PANELS





EXAMPLE

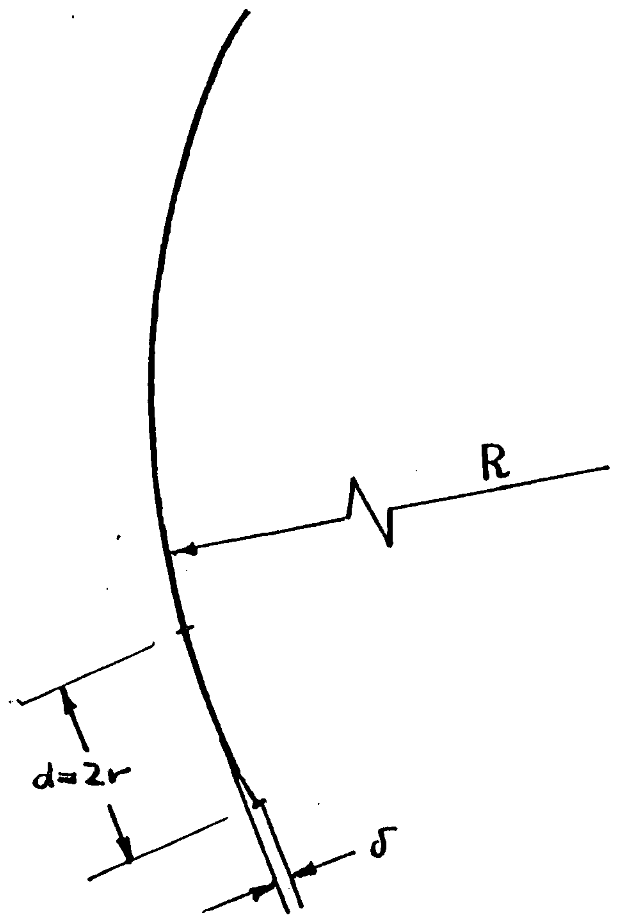
$$\cdot\ Q = \frac{d^2}{8R}\ \frac{\Delta R}{R}$$

$$\& \ Q \equiv .028\lambda \quad \& \ \lambda = 30\ \mu m \quad \therefore Q = .84\ \mu m$$

$$R = 40$$
$$d = 1.5$$

$$\therefore \frac{\Delta R}{R} = .84 \times 10^{-6} \times 8 \times 40 / 1.5^2$$

$$\boxed{\frac{\Delta R}{R} = 119 \times 10^{-6}}$$



$$\left\{\begin{array}{l} \delta = \dfrac{r^2}{2R} \\[2ex] \Delta\delta \equiv Q = -\dfrac{r^2}{2R}\left(\dfrac{\Delta R}{R}\right) \end{array}\right.$$

$$\left\{\begin{array}{l} \boxed{\Delta WF = \dfrac{1}{3.4}\ \dfrac{r^2}{R}\left(\dfrac{\Delta R}{R}\right)} \quad \text{SEE PRIOR BRIEFINGS} \\[2ex] \dfrac{\Delta R}{R} = \dfrac{3.4\ \Delta WF\ R}{r^2} \end{array}\right.$$

$$\therefore\ Q = -\frac{r^2}{2R} \times \frac{3.4\ \Delta WF\ R}{r^2}$$

$$\boxed{Q \cong 1.7\ \Delta WF}$$

or

$$\Delta WF = \frac{Q}{1.7}$$

WAVEFRONT ERROR & QUILTING AMPLITUDE

GLASS HOMOGENEITY REQUIREMENTS

- AXIAL HOMOGENEITY

$$\Delta\alpha' \leq \frac{3\,\Delta WF_{rms}\,h}{r^2\,\bar{\Delta T}}$$

- PART-TO-PART HOMOGENEITY

$$\Delta\bar{\alpha} \leq \frac{3\,R\,\Delta WF}{r^2\,\bar{\Delta T}} = 1e^{-6}/{}^\circ F \quad \text{TYPICAL}$$

(NO PROBLEM)

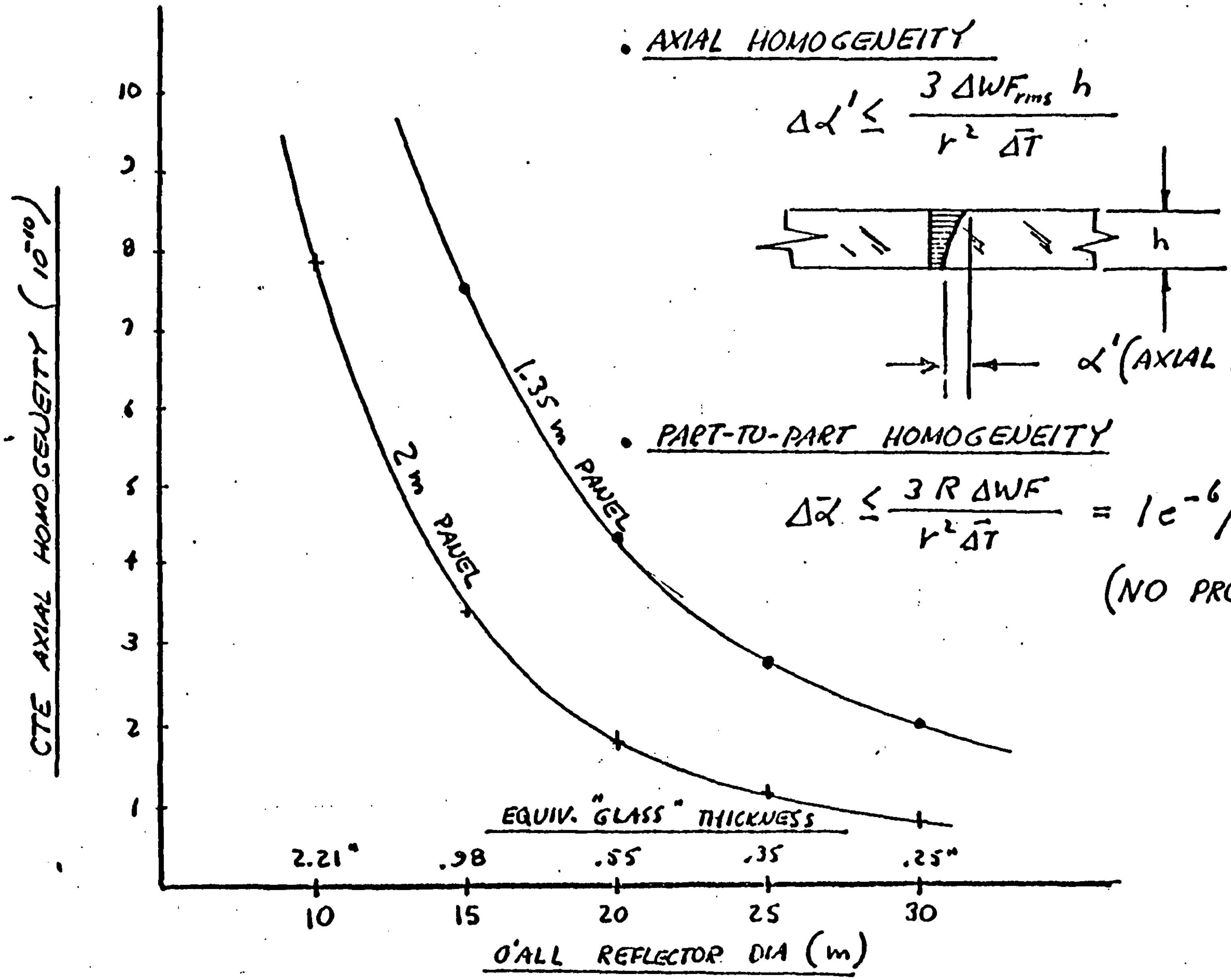
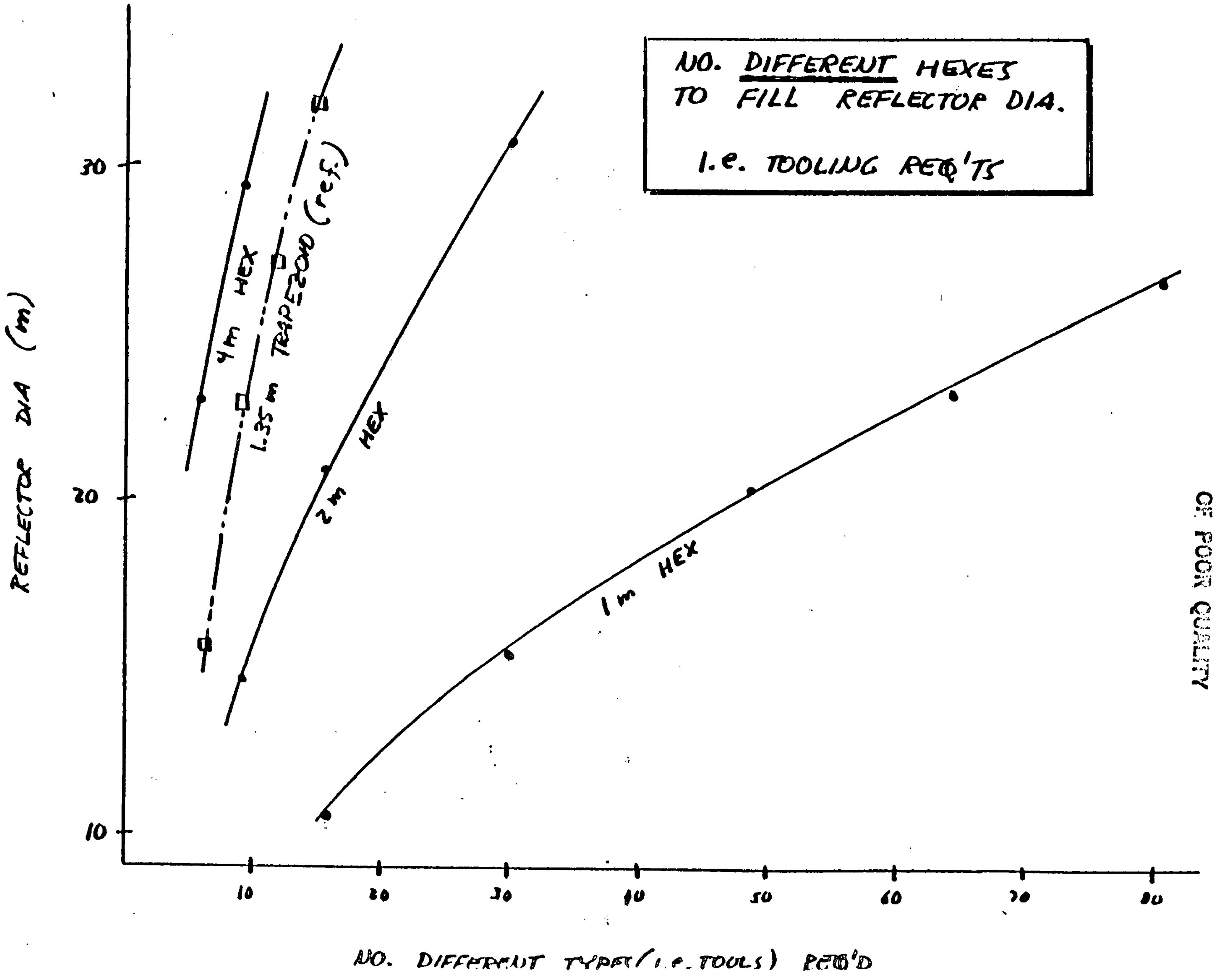


Fig 5

(12)


NO. DIFFERENT HEXES TO FILL REFLECTOR DIA.
I.e. TOOLING REQ'TS
4m HEX
1.35m TRAPEZOID (ref.)
2m HEX
1m HEX
REFLECTOR DIA (m)
30
20
10
NO. DIFFERENT TYPES (I.e. TOOLS) REQ'D
10
20
30
40
50
60
70
80

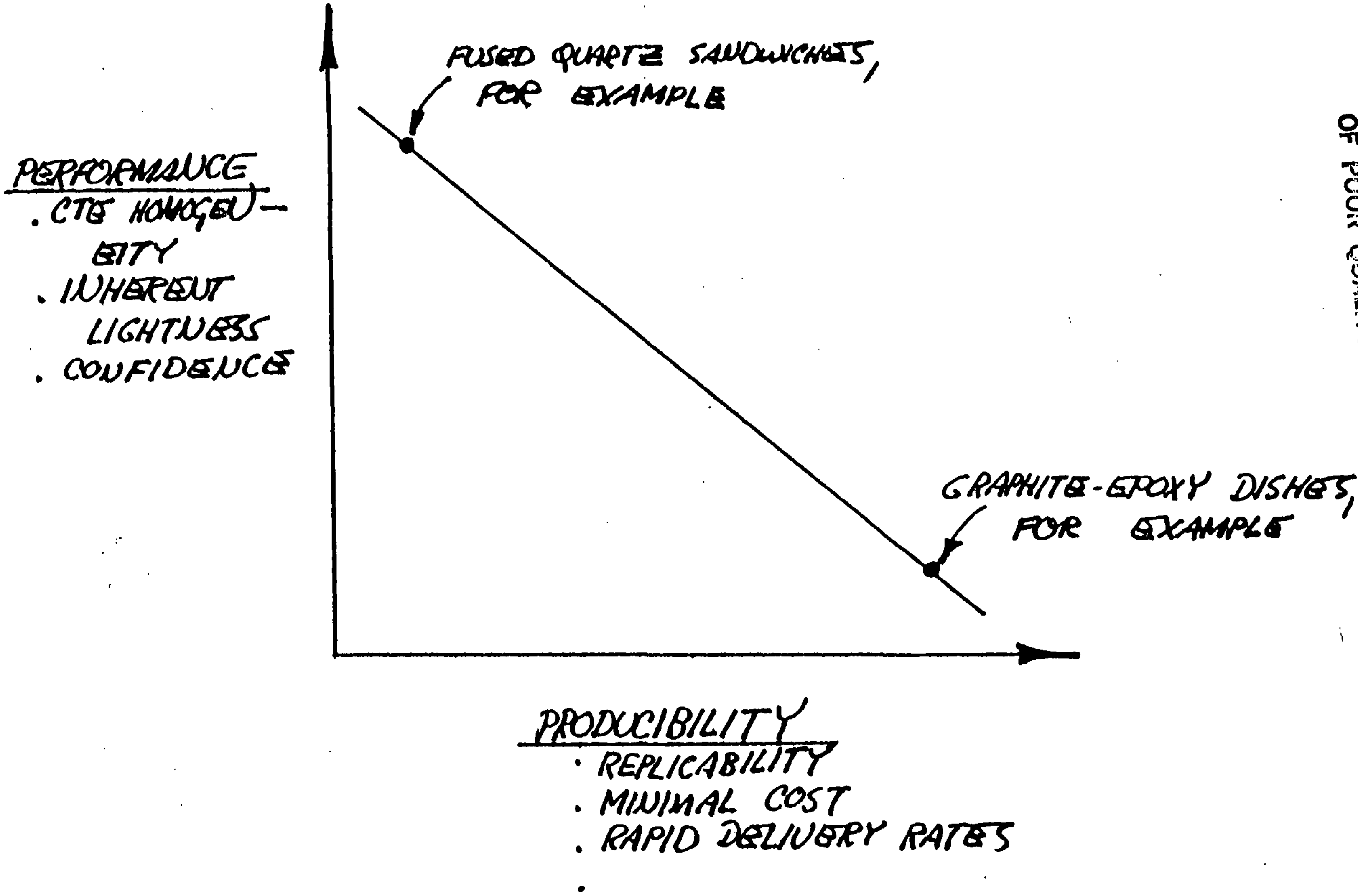
ASSESS EXISTING TECHNOLOGY

ASSESS EXISTING TECHNOLOGY

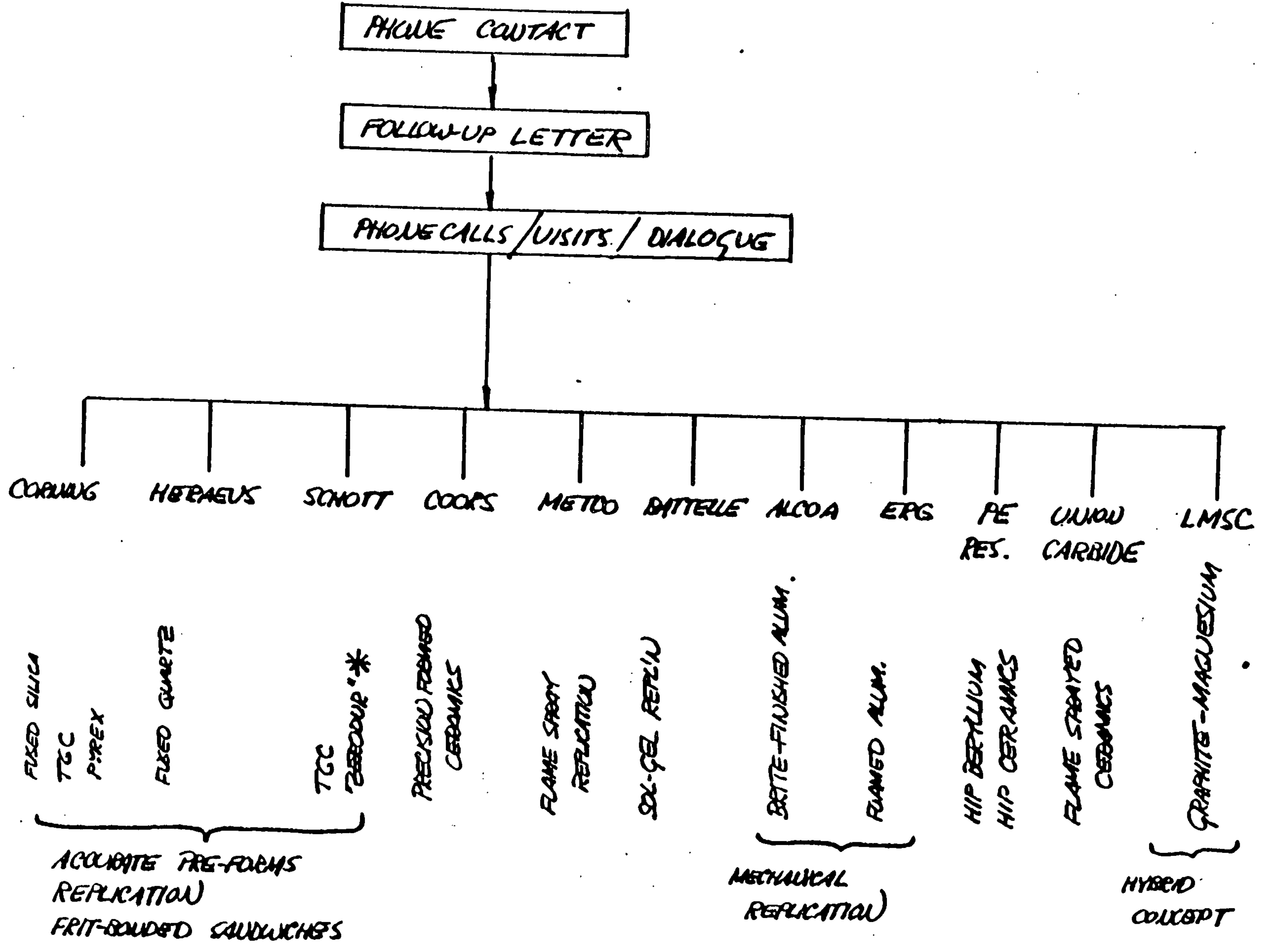
- ADEQUATE MATERIALS EXIST
  - HOMOGENEOUS
  - ISOTROPIC
  - IN PRODUCTION

- FULLY PROVEN PRODUCIBILITY METHODS DON'T
  - REPLICABILITY 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



POTENTIAL SUPPLIER CONTACTS



* DARPA TECHNOLOGY @ 85

Tab 3-

CANDIDATE MAT'LS	CONFIG'N APPLICABILITY Δα SOLID	Δα S'WICH	Δα' SOLID	Δα' S'WICH	FORMING TEMP	FRITS, ADHESIVES	DELIVERY RATE	CURRENT SIZE LIMIT	COST	2μ PERF.
HERAEUS FUSED QUARTZ		✓	✓		2000°C	NO	SL.	44"	H	YES
SCHOTT ZERODUR		✓	✓		800°C*	YES	F.	250"	H	YES
CORNING PYREX		(✓)	?		~	YES	(F.)	?	L	?
CORNING "ALUMINA SILICATE"	?		?		600°C	YES	?	?	?	?
HIP BERYLLIUM			?		~800°C	NO	(F.)	48"	M/H	~YES
"COILZAK"/AL. FOAM		(✓)	N/A		RT	YES	F	80"	VL	NO

CANDIDATE MAT'LS & PRODUCIBILITY FACTORS

* SUBS. CERAMMING REQ'D

HERAEUS FUSED QUARTZ

- MOST HOMOGENEOUS MAT'L AVAILABLE }
- NO PERCEPTIBLE ANISOTROPY } OPTOSIL—III
- α/K IS OK
- THIN QUART SHELLS HAVE BEEN FORMED
- 3-4% AREAL DENSITY CORES HAVE BEEN MADE
- VERY HIGH COMPANY INTEREST

SCHOTT ZERODUR

- 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 $\Delta\alpha'$ INVESTIGATIONS REQ'D FOR SOLIDS
- LOW TEMP FRIT DEVEL. REQ'D FOR SANDWICHS
- PROBABLY A GOOD CHOICE BUT REQUIRES UP-FRONT COSTS FOR MAT'L & PROCESS DEVELOPMENTS
  - FORMING
  - JOINING
  - CTE "TUNING"

CORNING PYREX & ALUMINA SILICATES

- GOOD POTENTIAL FOR "EL CHEAPO" MIRRORS
- NOT MUCH DETAIL DATA AVAILABLE ON SPECIFIC MAT'L CHARACTERISTICS
- PYREX PREFORMS & FRIT 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 PERKIN-ELMER

- EXCITING NEW DEVELOPMENTS AT PE
- SMALL SCALE PIECES SHOW FIGURE REQ'TS BE MET AT 200°K, $\underline{\Delta R}$ DATA LACKING
- WILL MAT'L BE SUFFECIENTLY HOMOGENEOUS & ISOTROPIC AT 3 TO 5 TIMES SCALE-UP ?
- CONSIDERABLE GOV'T INTEREST
- THIS ONE IS DEFINITELY WORTH WATCHING !!

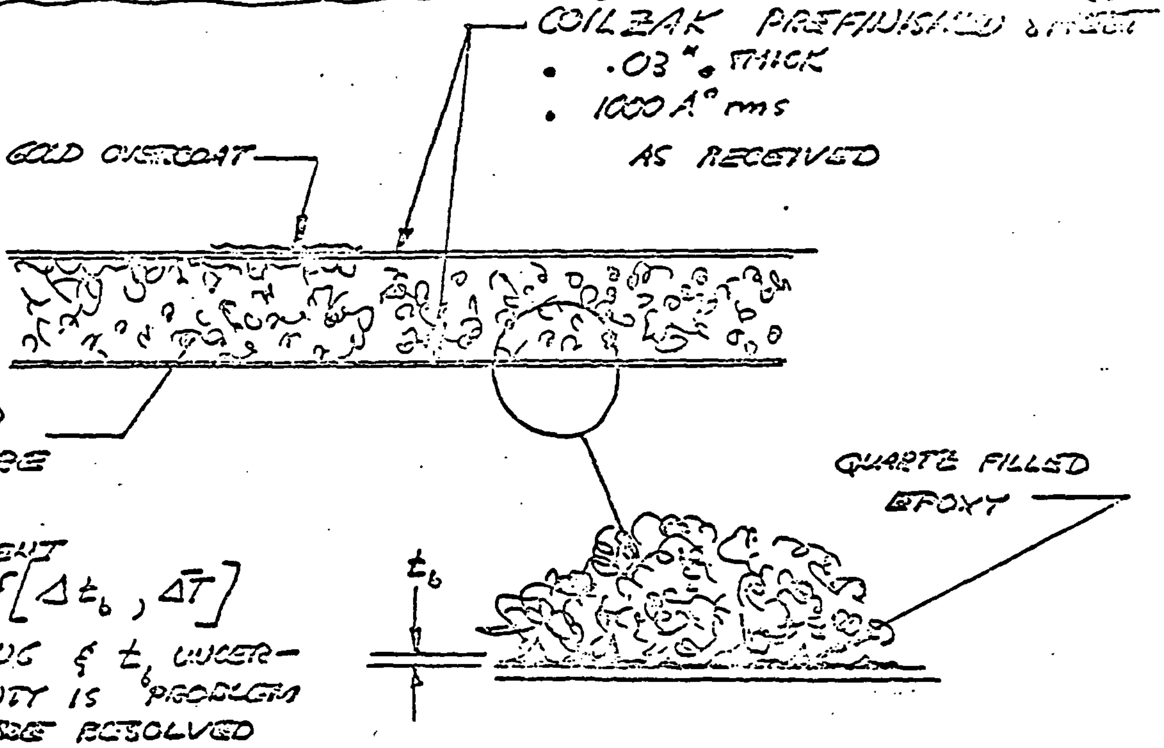
ALCOA "COILZAK" & ERG ALUMINUM FOAM

- 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:
    - 8×10^{-6} WAVINESS FOR 2 μ PERF.
    - 100×10^{-6} " " 30 μ PERF.

㉔

FIG. 9 "STAMPED" METAL MIRROR

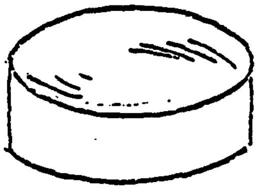
FIG. 9



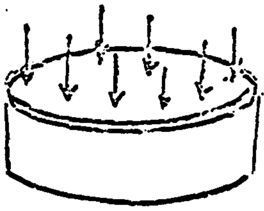
THERMAL MOMENT

$M_T = f[\Delta t_b, \Delta T]$

WICKING & t_b UNCERTAINTY IS PROBLEM TO BE RESOLVED

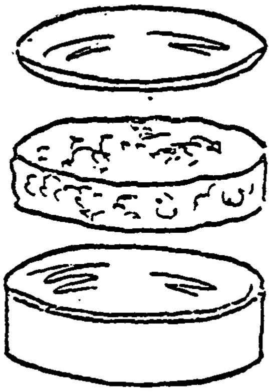


FORMING DIE OF CORRECT RADIUS & OPTICAL PRESCRIPTION

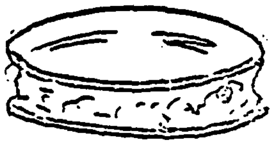


FORMING THE FACESHEETS

.03 ALUMINUM COILBAK FACESHEET.

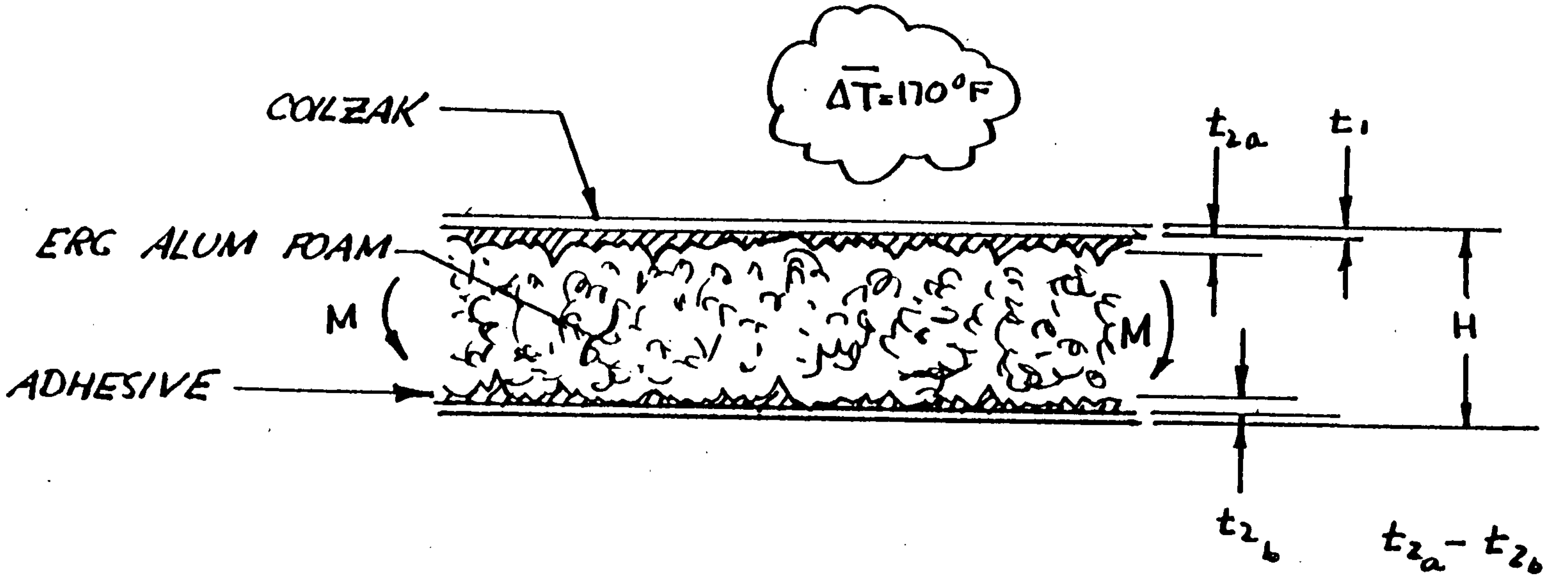


ASSEMBLING THE SANDWICH ON THE FORMING DIE



FINISHED ALUMINUM MIRROR READY FOR OPTICAL COATING

COILZAK/ALUMINUM MIRRORS: THE Δt_2 BONDLINE ISSUE



$t_{2a} - t_{2b} \equiv \Delta t_2$

$$M \cong \frac{(\alpha_2-\alpha_1)\, t_1\, \overline{\Delta T}}{2\left(\frac{1}{t_1 E_1} + \frac{1}{\Delta t_2 E_2}\right)}$$

$\alpha_1 = 12\times10^{-6}$
$\alpha_2 = 25\times10^{-6}$

$E_1 = 10\times10^6$
$E_2 = .5\times10^6$

$t_1 = .02''$
$\Delta t_2 = ?$

$$\therefore \boxed{M \cong 11\, \Delta t_2 \text{ in-lbs}}$$

$$\left.\begin{aligned} &\delta = \frac{r^2}{2R} \;\; \& \;\; \Delta\delta = -\frac{r^2}{2R}\left(\frac{\Delta R}{R}\right) \\ &\Delta\delta = \frac{Mr^2}{2E_1 I} \;\; \& \;\; I = \frac{t_1 H^2}{2} \end{aligned}\right\} \boxed{\Delta t_2 \le \left(\frac{E_1 t_1 H^2}{22R}\right)\frac{\Delta R}{R}}$$

ALLOWABLE Δt_2 VALUES, AN EXAMPLE

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

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

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

	H			
t_1	1	2	3	4
.01 in.	.00036 in.	.0014	.0032	.0056
.015	.00054	.002	.0048	.0084
.02	.0072	.0028	.0064	.011
.025	.0009	.0035	.008	.014
.03	.001	.0042	.0096	.017
Kg/m²	6 → 8	11 → 13	16 → 18	21 → 23

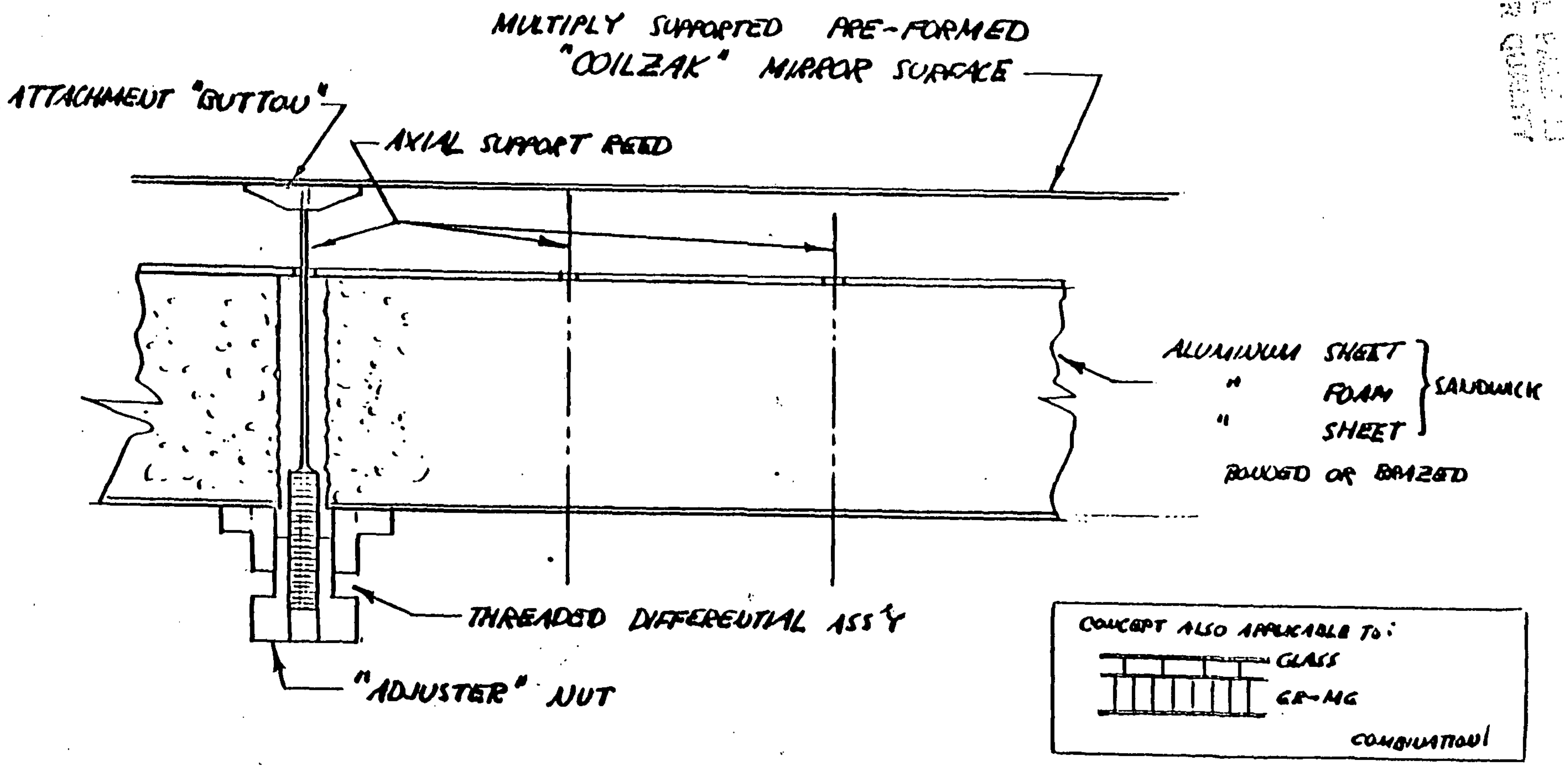
Δt_2 PROBABLY OK
BUT
NO Kg/m² PAYOFF!

COILZAK MIRRORS / CONCLUSIONS

- Δt_2 CONTROL @ $\lambda = 30\ \mu m$ 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 COHERENT WAVEFRONT PERFORMANCE

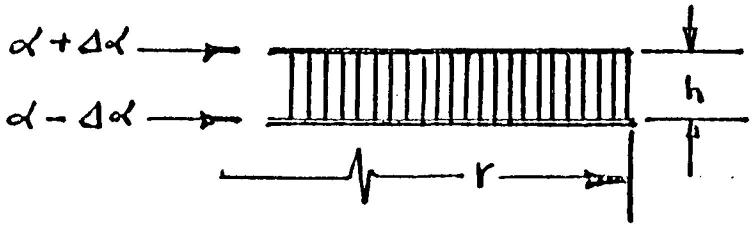


2/11/82

57

COMPOSITES WERE ALSO EVALUATED

- THEY DID NOT PASS THE $\Delta R/R$ CRITERION FOR COHERENT OPERATION
- PROBLEM LIES WITH PART-TO-PART CTE VARIABILITY



$\Delta \bar{T} \tilde{=} 170°F$

2r	h			
	4"	8"	12"	16"
40"	.004	.008	.012	.016
60"	.0018	.0035	.0053	.007
80"	.001	.002	.003	.004

MAX $\Delta\alpha$

(ppm/°F)

TYPICAL "BEST EFFORT" RESULTS	
ST METERING TRUSS	.03
ST FINE GUIDANCE SENS.	.04
ST FOCAL PLANE STR	.12

ACHIEVABLE $\Delta\alpha$ PRECISION

(ppm/°F)

Figure 10

ORIGINAL PAGE IS OF POOR QUALITY

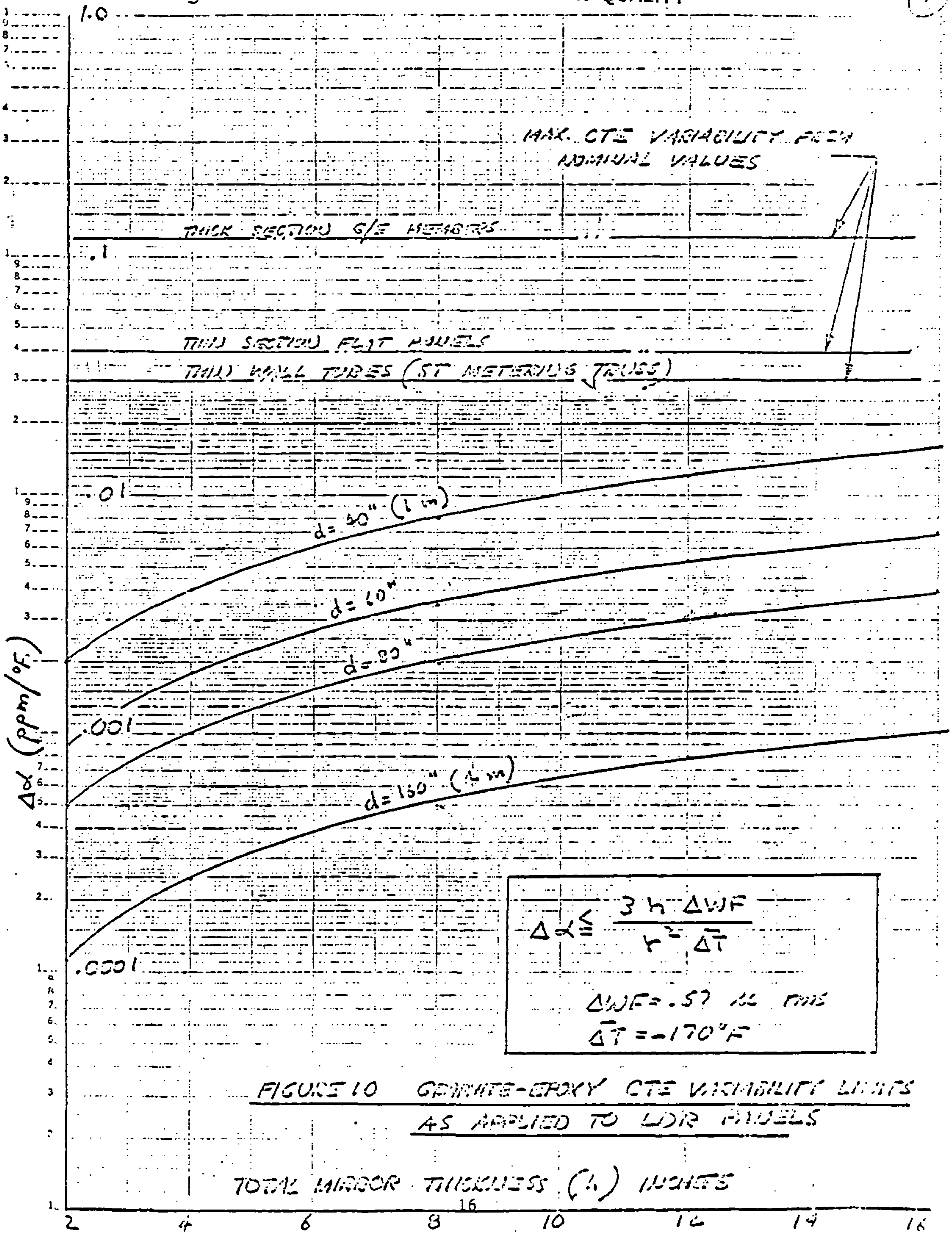


FIGURE 10 GRAPHITE-EPOXY CTE VARIABILITY LIMITS AS APPLIED TO LDR PANELS

ANALYTIC STUDIES AND PERFORMANCE PREDICTIONS

ANALYTIC STUDIES & PERFORMANCE PRED'NS

- THERMAL ENCLOSURE CRITICAL TO PERFORMANCE

  "CHALLANGES".....
  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 TRAPEZOIDS DON'T CURL

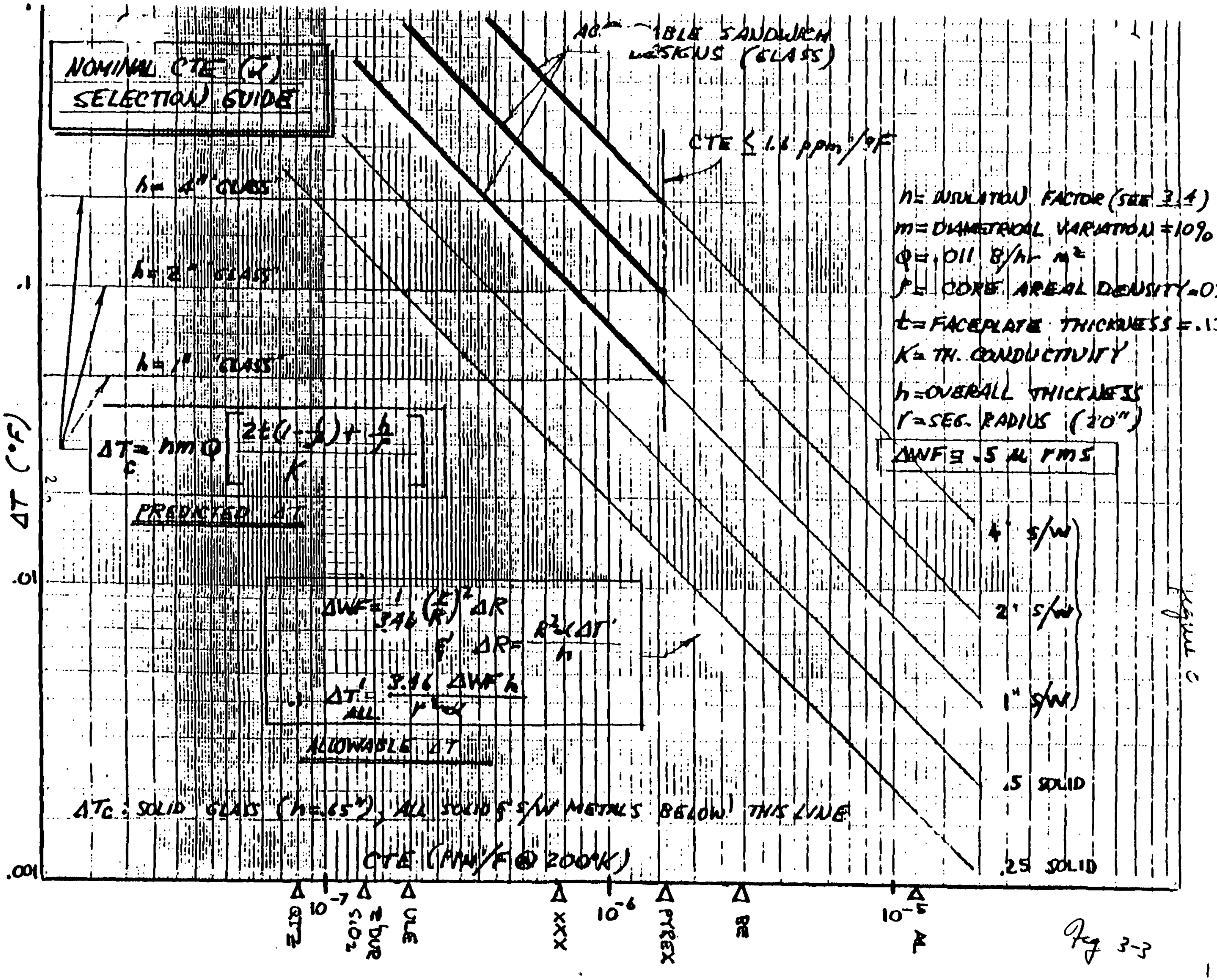


figure c

Fig 3-3

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

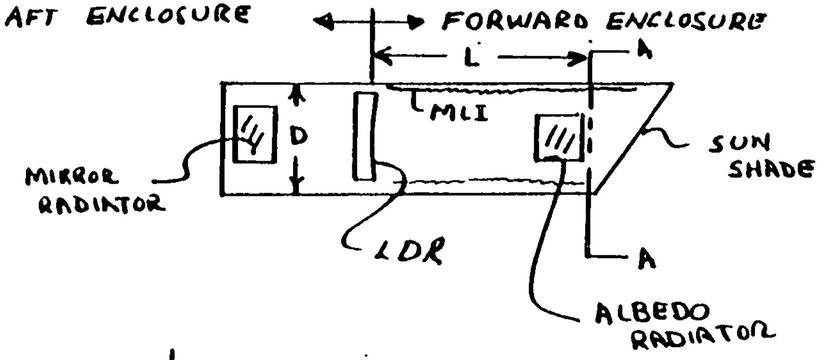
DETERMINE PASSIVE ENCLOSURE DESIGN

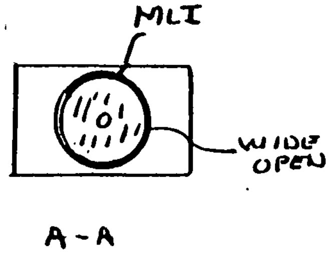
ANALYZE MIRROR SEGMENTS

STATUS

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

R.G.B. 2/23/82



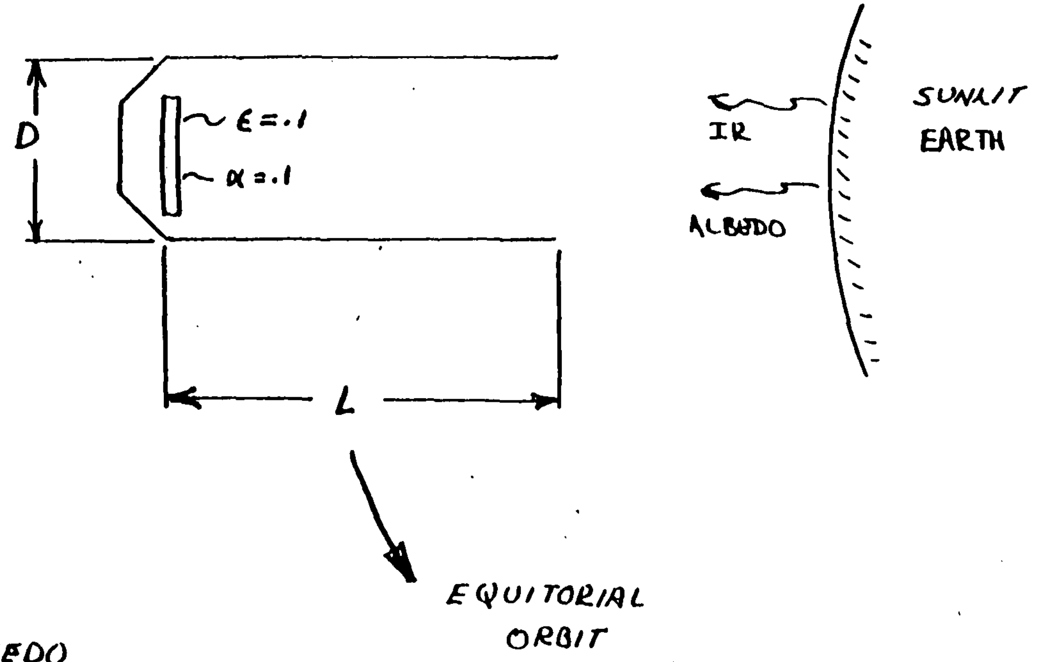


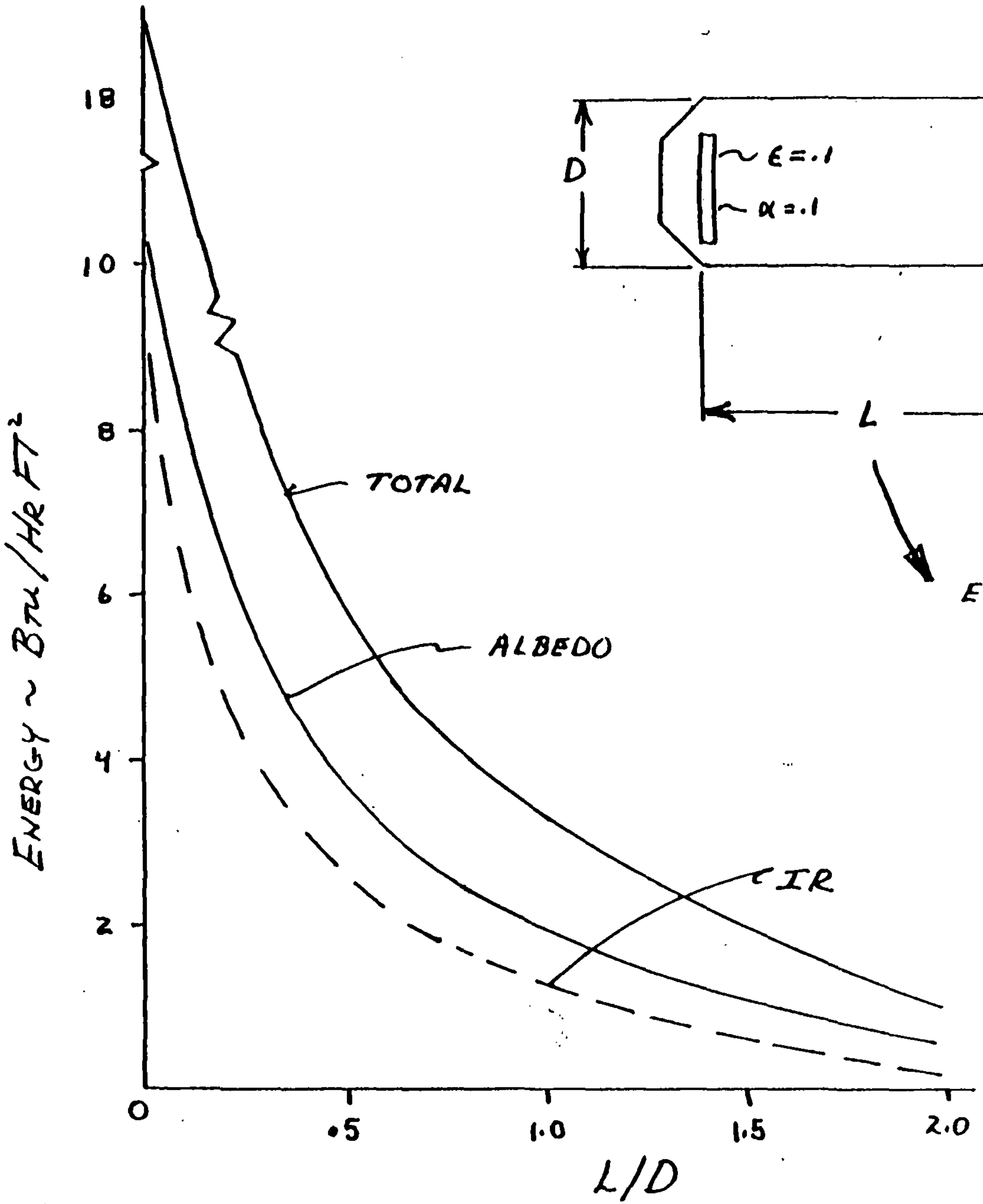
PARMETER	
FORWARD ENCLOSURE LENGTH (L)	CONTROLS ENERGY IRRADIATING/ABSORBED BY THE LDR
ENCLOSURE MLI	MINIMIZES SIDE TO SIDE GRADIENTS WITH MLI MAXIMUM GRADIENT CHANGE < 1°F
RADIATOR RADIATOR/SHADE	PROVIDES AN AREA FOR EARTH IR AND ALBEDO ENERGY REJECTION
SUN SHADE	ELIMINATES THE POSSIBILITY OF THE SUN IRRADIATING THE INTERIOR OF THE FORWARD ENCLOSURE
MATERIAL ABSORBTIVITY (α) EMISSIVITY (ϵ)	THERMAL RADIATION PARAMETERS • EXTERNAL ENCLOSURE $\alpha/\epsilon = .2/.8$ • LDR $\alpha/\epsilon = .1/.1$ • INTERNAL ENCLOSURE $\alpha/\epsilon = .8/.8$

$\Delta T(s)$ background

LDR ENCLOSURE DESIGN CONCEPT

MAXIMUM ENERGY ABSORBED BY THE REFLECTOR





FLUX LOAD

SOLAR	457	BTU/HR FT²
EARTH IR	87	BTU/HR FT²
EARTH ALBEDO	192	BTU/HR FT²

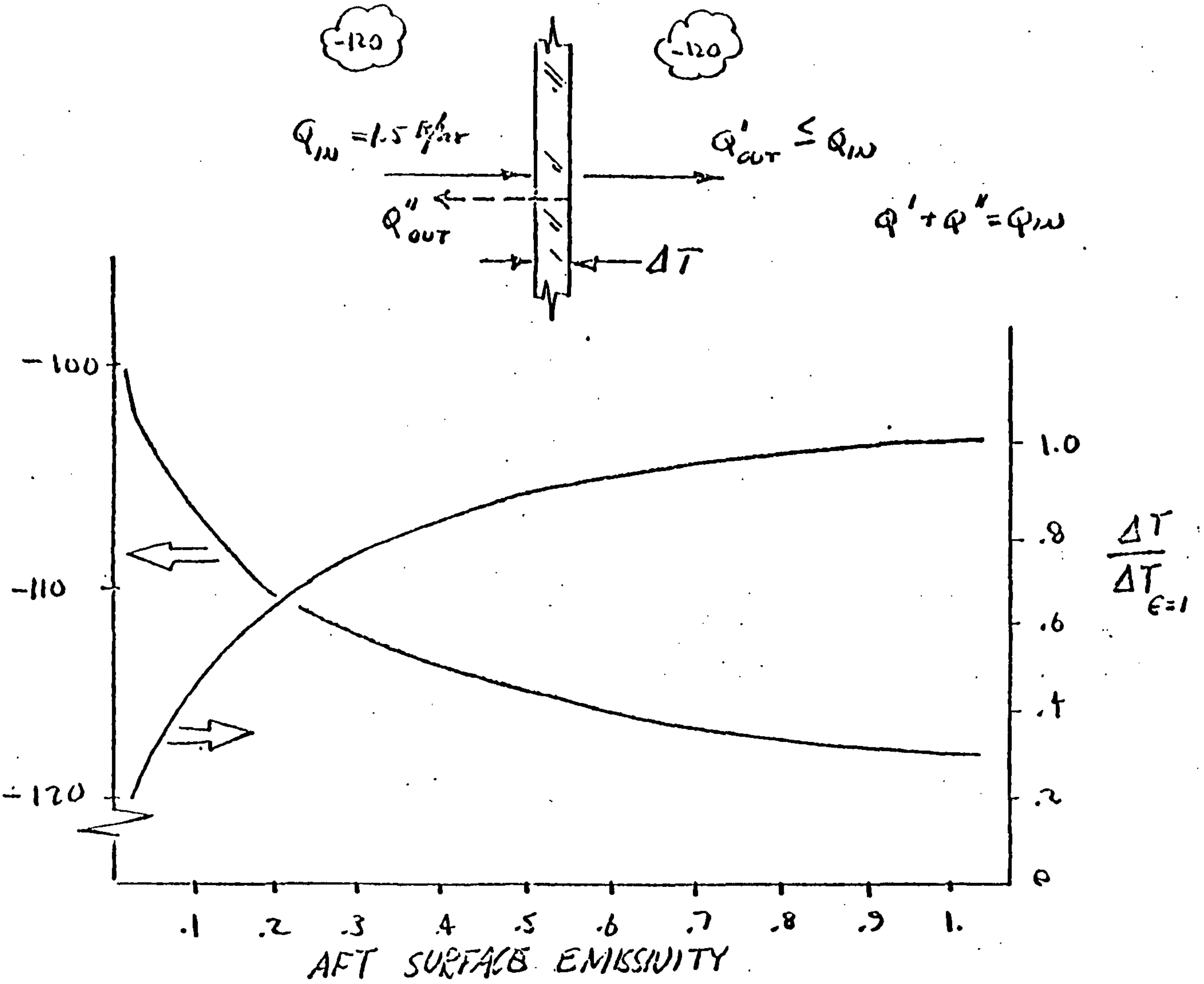


Fig. 7

Figure 1

LDR ENCLOSURE TEMPERATURE

- FORWARD ENCLOSURE TEMPERATURE

CONFIGURATION / TEMPERATURE ~ °F

	MAXIMUM	MINIMUM	AVERAGE
NO RADIATOR	83	-460	-145
ALBEDO RADIATOR	44	-225	-114
MOVEABLE SHADE	-105	-127	-120

- AFT ENCLOSURE TEMPERATURE

CONFIGURATION / TEMPERATURE ~ °F

	MAXIMUM	MINIMUM	AVERAGE
NO RADIATOR	83	-460	-145
ALBEDO RADIATOR	-105	-127	-120
MOVEABLE SHADE	-460	-460	-460

- ABSORBED ENERGY

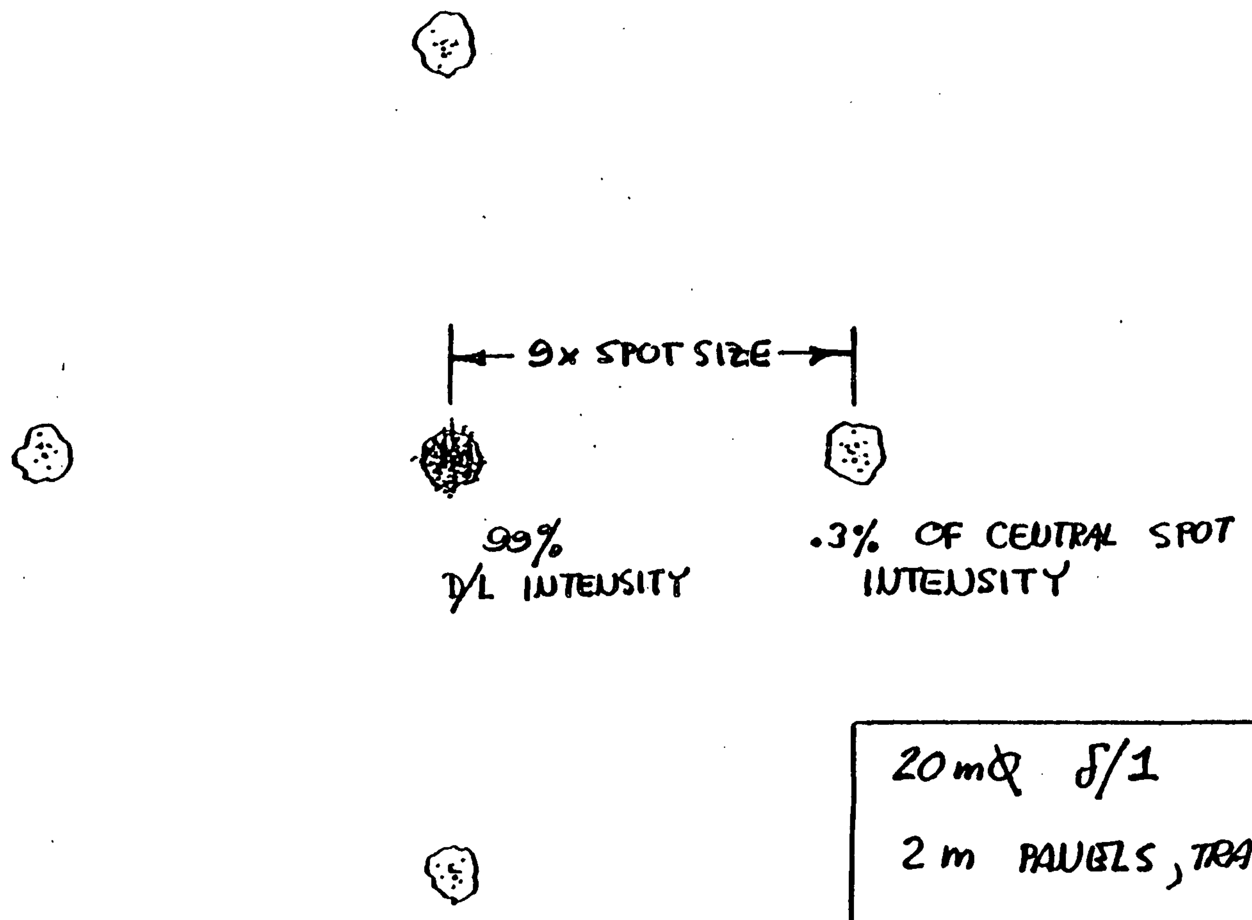
MAXIMUM 1.5 BTU/HR FT^2

SIDE TO SIDE VARIATION $\approx$ 10%

- SIDE TO SIDE GRADIENT

LESS THAN 1°F

INFLUENCE OF ΔR/R ON AN OTHERWISE ~~PERFECT~~ IMAGE



20 mØ f/1

2 m PANELS, TRAPEZOIDS

$\lambda = 30\ \mu m$

$\lambda/30$ P-P "QUILTING" ERROR,
i.e. ΔR/R → .5μ rms WF

DESIGN DEFINITION AND CONCEPT SELECTION

DESIGN DEFINITION & CONCEPT SELECTION

- HERAEUS FUSED QUARTZ
  - ULTRA LIGHT 15 Kg/m^2 OPTIMIZED SANDWICH
  - PLUS .....
    - OPTICAL STYLUS
    - QUILTING POST
    - SEMI-REPLICATED BLANK

    } PRODUCIBILITY

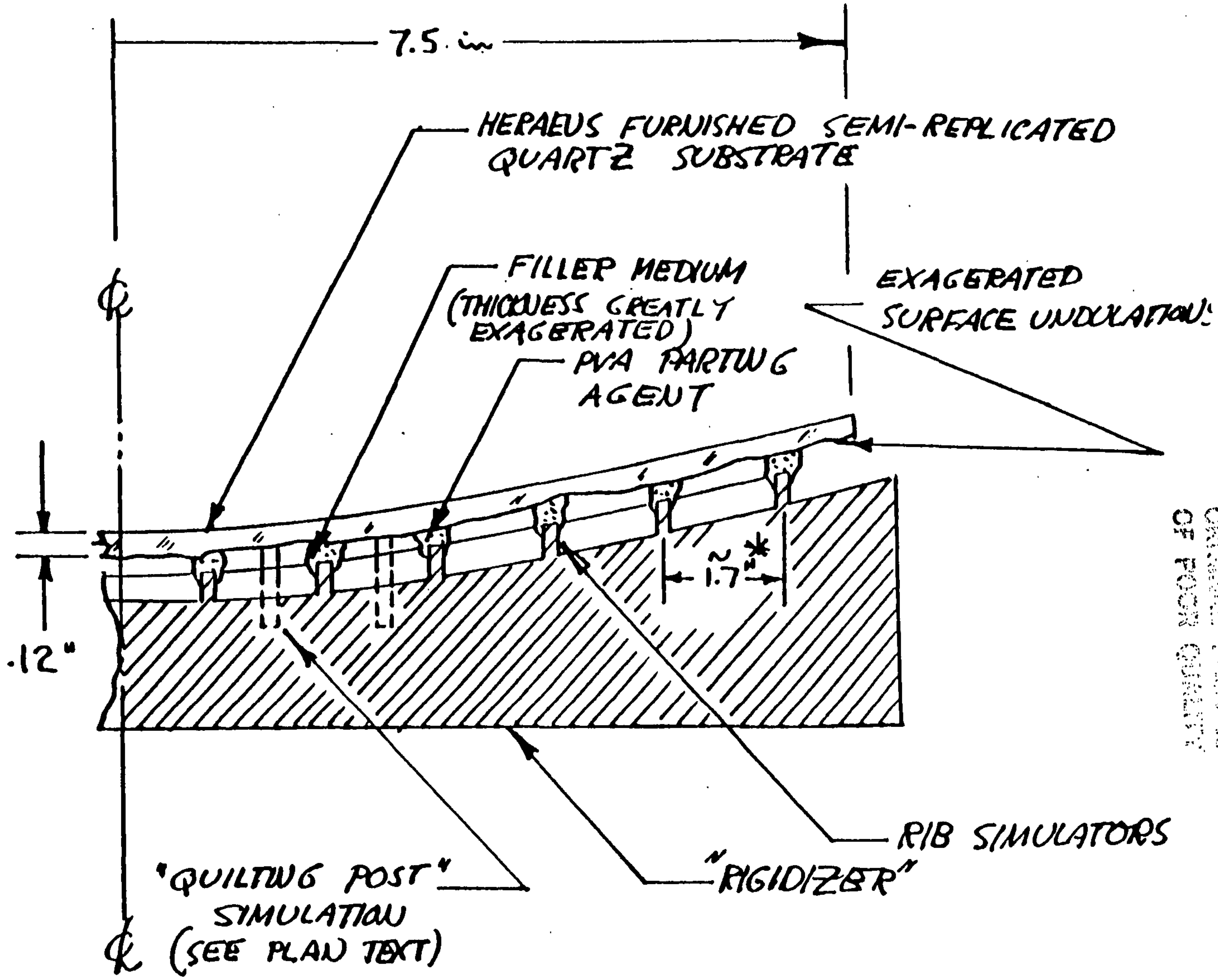
- ALTERNATE MATERIAL CHARACTERIZATION TEST
  - HOMOGENEITY
  - FORMABILITY
  - JOINABILITY
  - $\Delta\alpha'$

SELECTION LOGIC

- EMPHASIS IS ON SANDWICH CONFIGURATIONS
- LITTLE ENTHUSIASM FOR THIN PASSIVE SOLIDS OUTSIDE OF THE LDR COMMUNITY (& MYSELF)
- AND WE'RE LOOKING FOR COMMUNITY-WIDE ~~FUNDING~~ SUPPORT
- 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

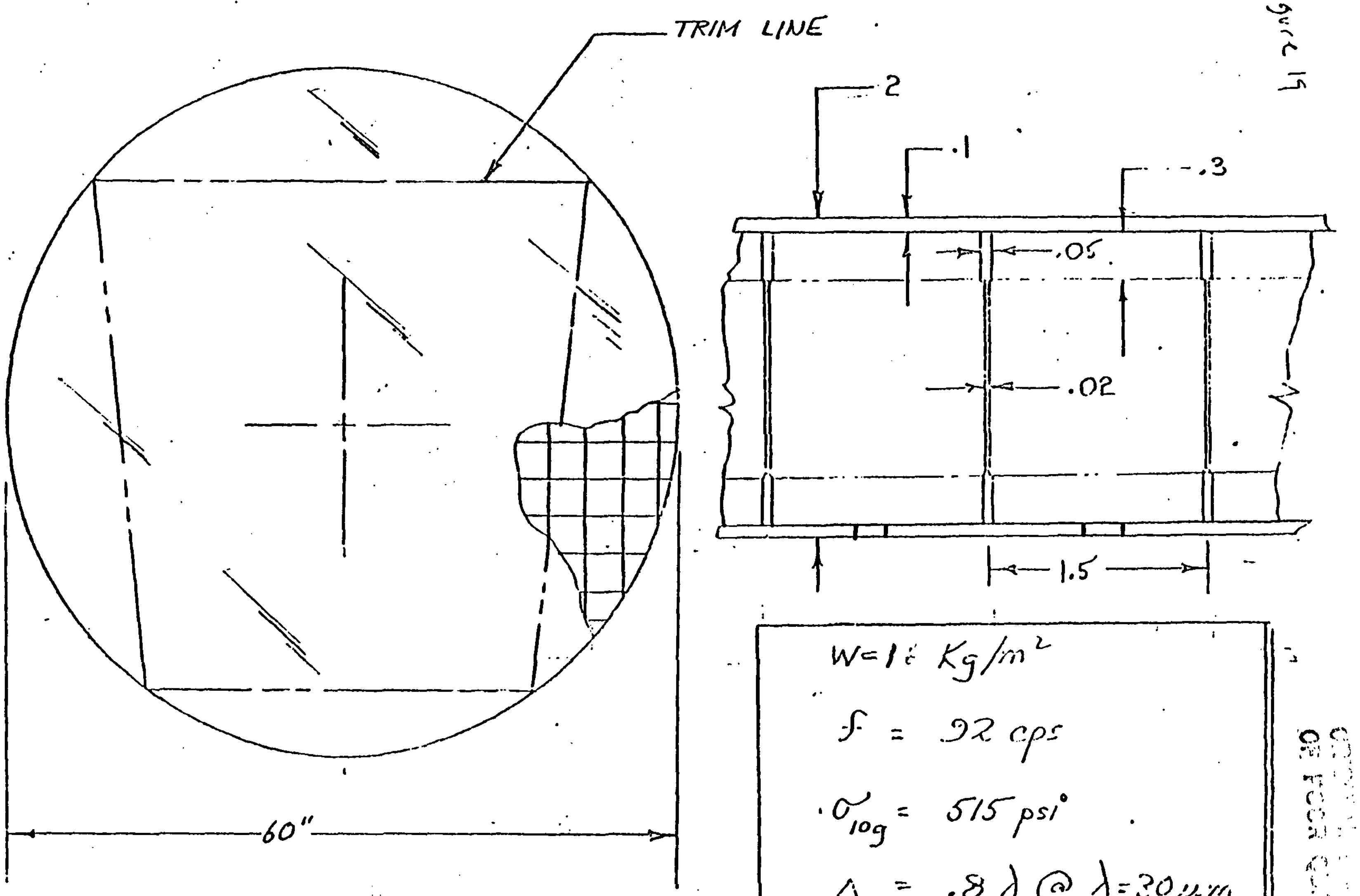


SHELL IN TOOLING FIXTURE
~ CONCEPT ONLY ~

NOT TO SCALE

* $S^4/t^3 = 5000$ SIMULATING
A FULL SCALE .1" FACEPLATE,
1.5" CELL MIRROR)

Figure 19



$W = 16\ Kg/m^2$

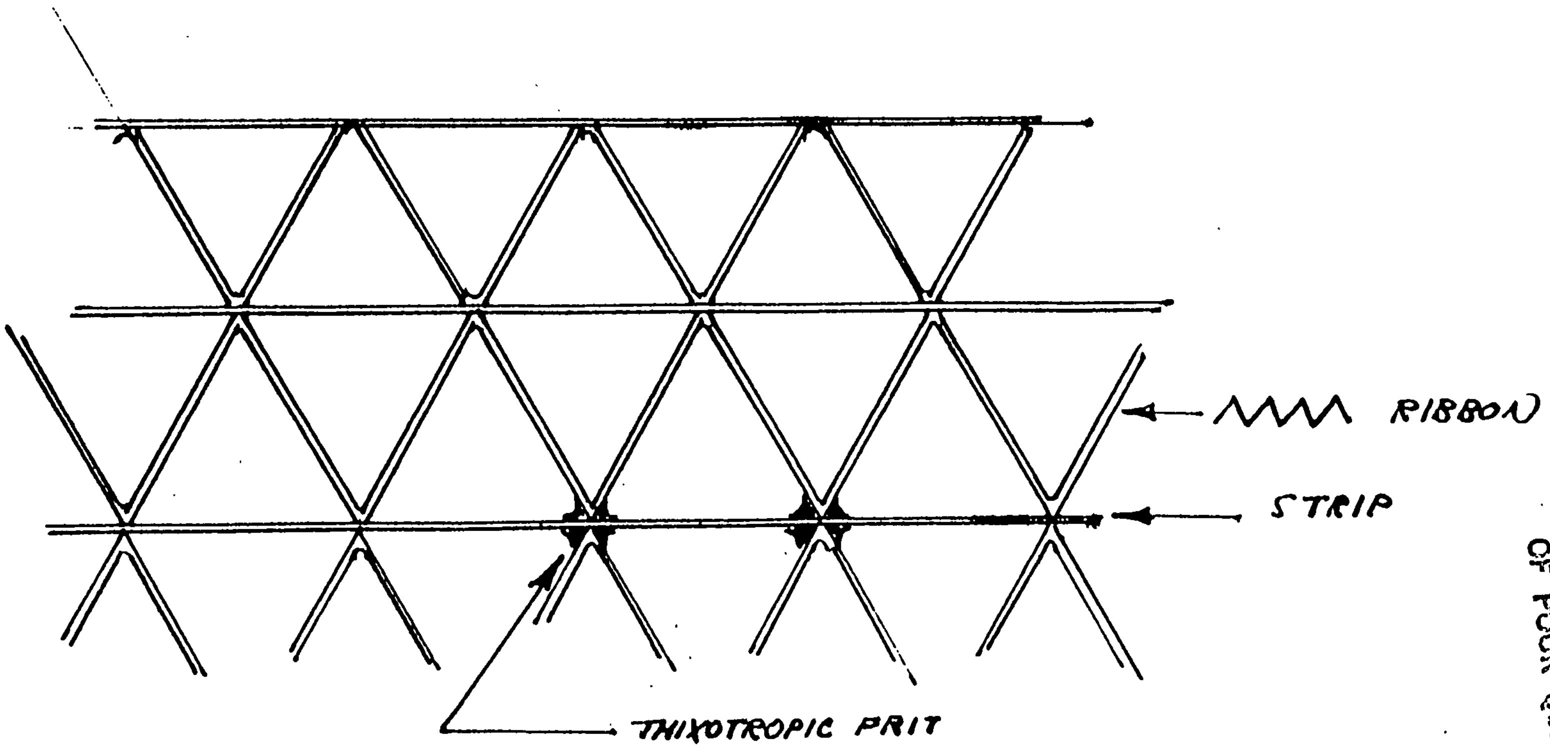
$f = 92\ cps$

$\sigma_{10g} = 515\ psi$

$\Delta_{ST} = .8\lambda\ @\ \lambda = 30\,\mu m$

MAT'L HERAEUS FUSED QUARTZ
CORNING ALUMINO-SILICATE

OPTIMAL LDR MIRROR PANEL



ISOTROPIC
BENDING PROPERTIES

PYREX
RIBBON CORE
MIRROR CONSTRUCTION

FEASIBLE BY VIRTUE OF PYREX'S
HIGHLY FORMABLE NATURE

C-4

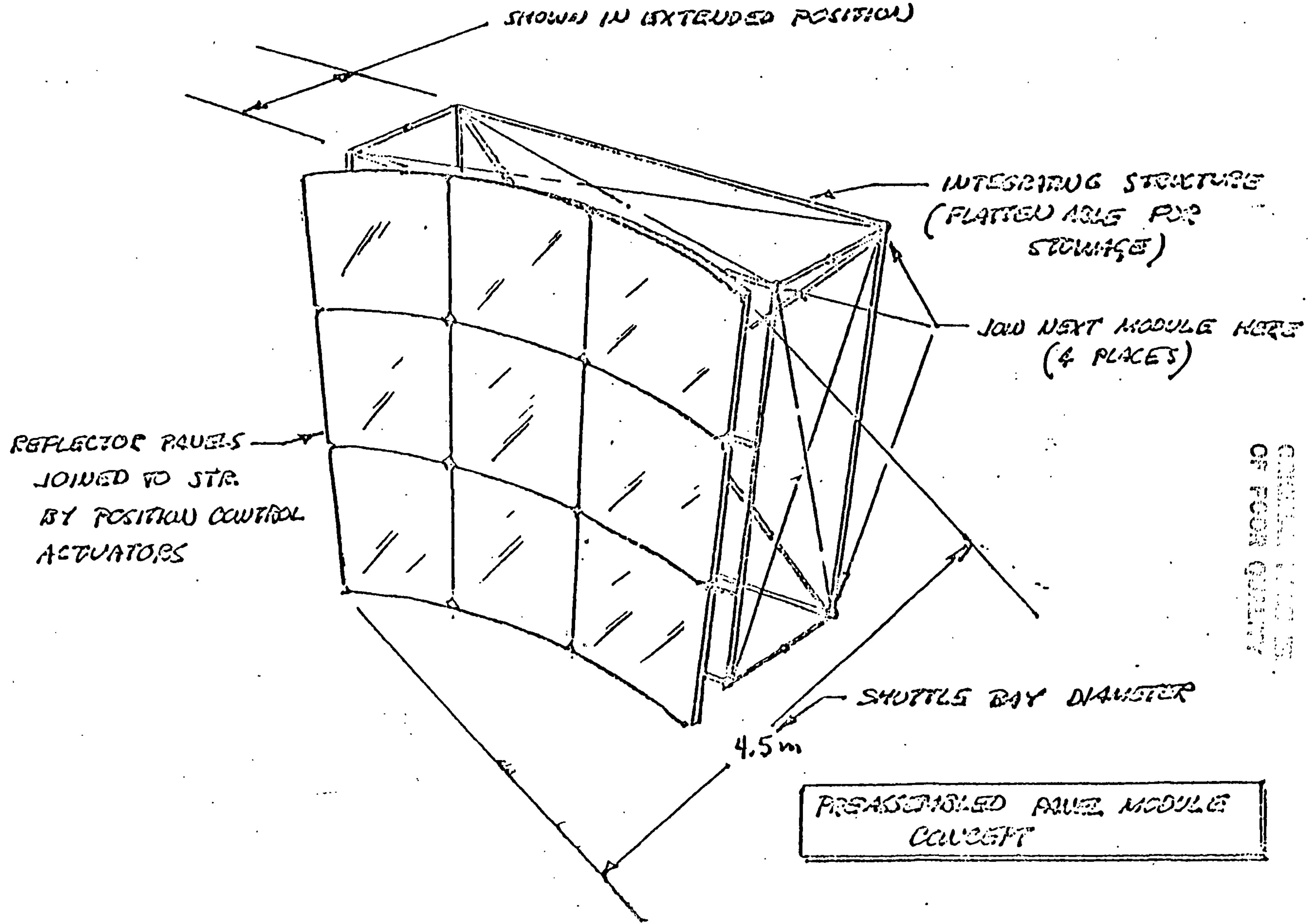
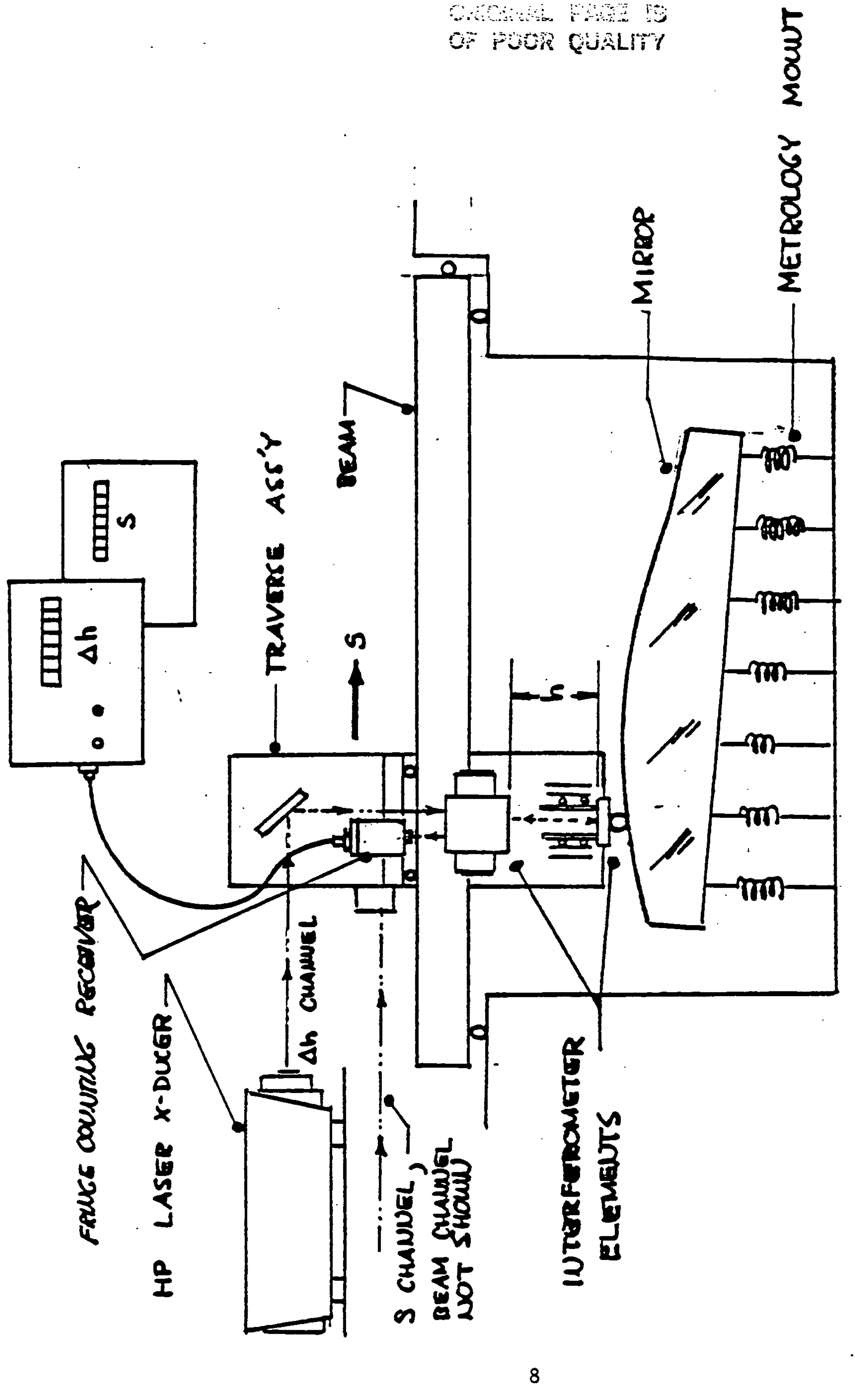

SHOWN IN EXTENDED POSITION
INTEGRATING STRUCTURE
(FLATTENABLE FOR
STOWAGE)
JOIN NEXT MODULE HERE
(4 PLACES)
REFLECTOR PANELS
JOINED TO STR.
BY POSITION CONTROL
ACTUATORS
SHUTTLE BAY DIAMETER
4.5 m
PREASSEMBLED PANEL MODULE
CONCEPT

Figure 6

ORIGINAL PAGE IS
OF POOR QUALITY

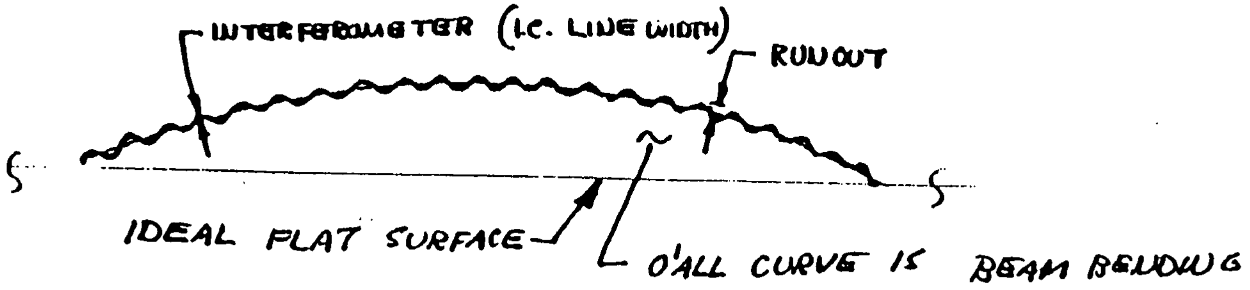


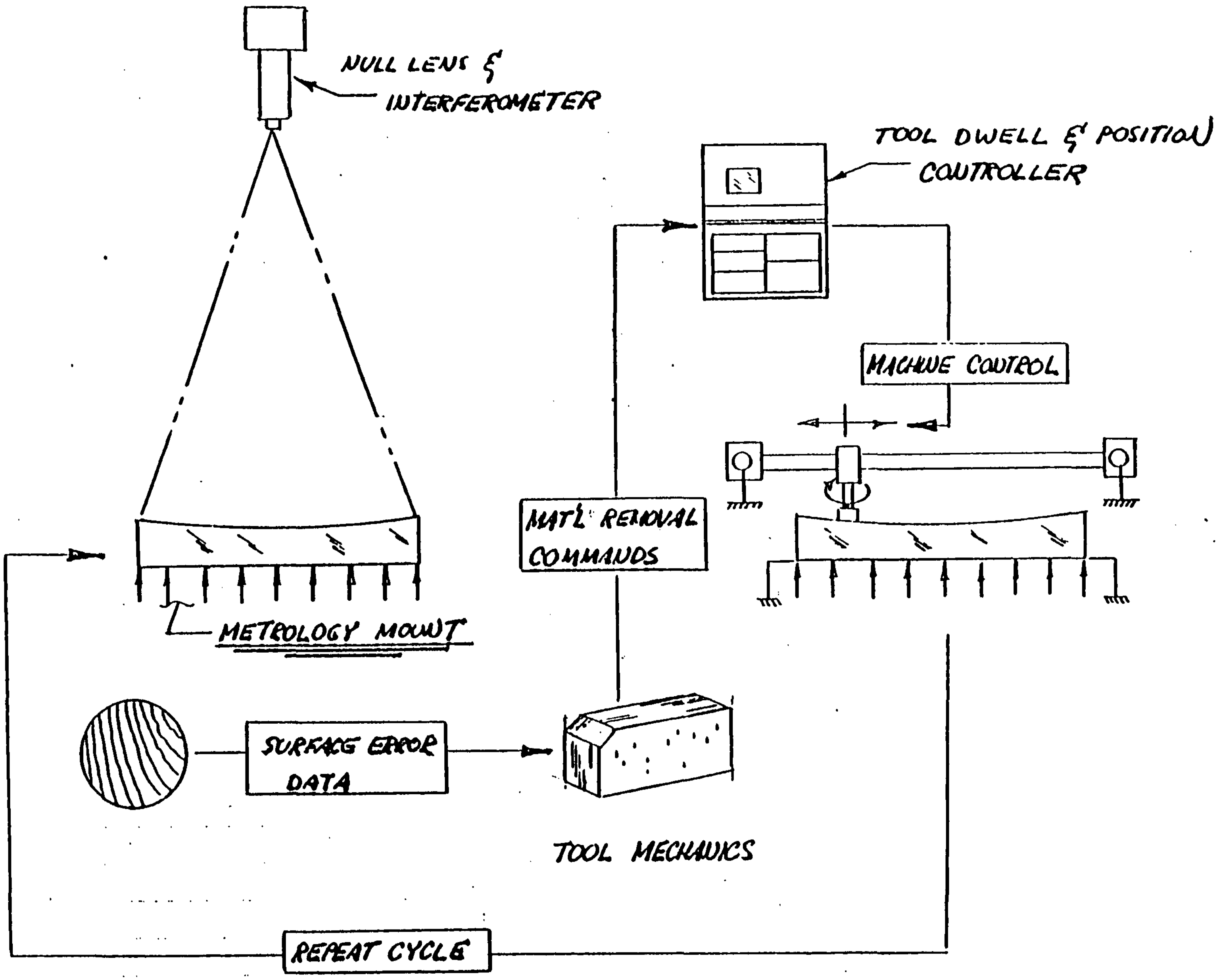
CONTOUR SENSING OF NON-SYMMETRIC CONVEX ASPHERIC OPTICAL SURFACES

OPTICAL STYLUS ACCURATE TO $\frac{\lambda}{50}$ rms AT $\lambda = 2.8\ \mu m$

LINEAR INTERFEROMETER...	$\pm 1.118 \times 10^{-6}$	
BEAM BENDING	$\pm 2 \times 10^{-6}$	(RESIDUAL CALIB'N ERROR)
ROLLER RUNOUT	N/A	(SEE FIGURE)

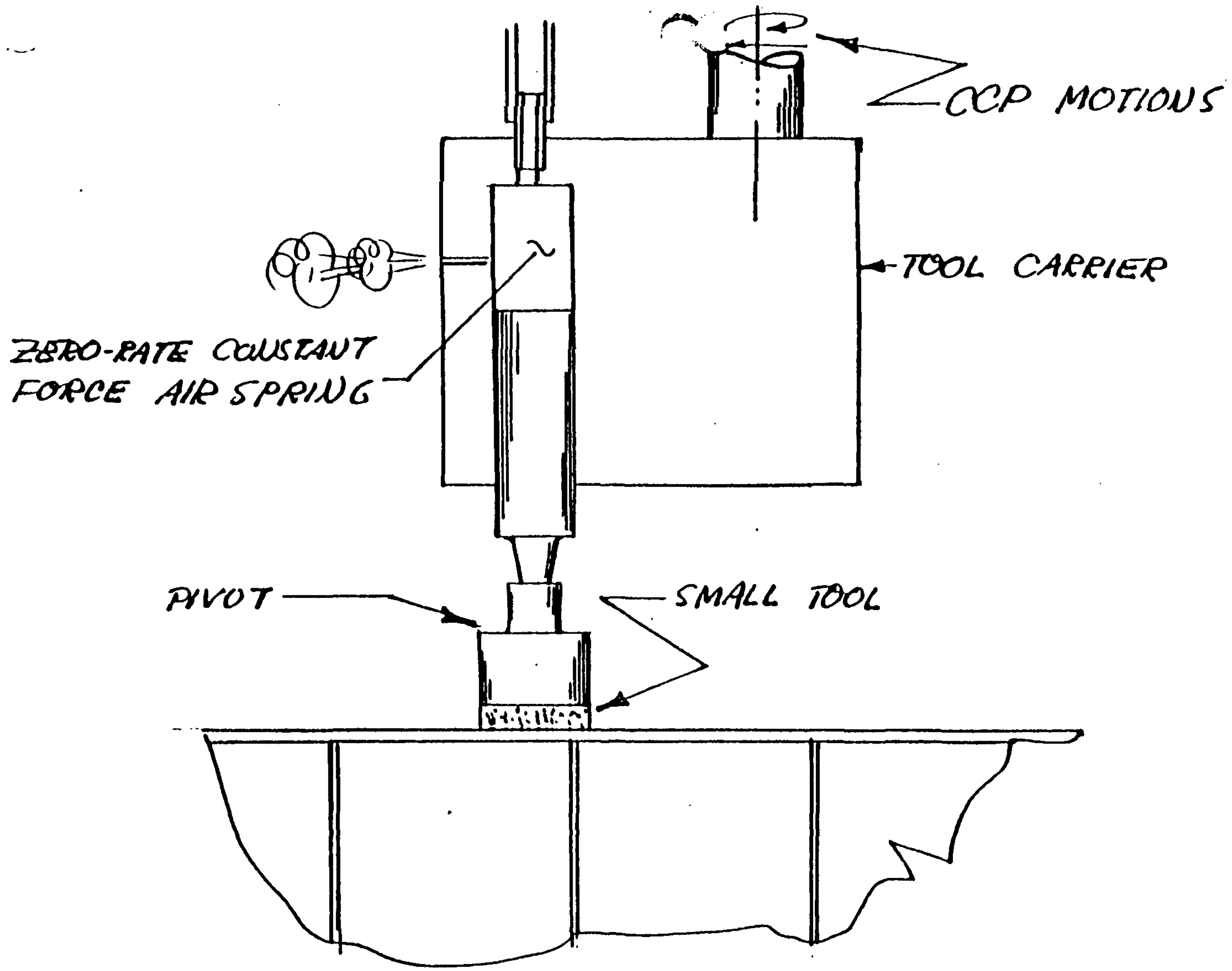
$$\Sigma = 2.29 \times 10^{-6} \text{ in} \quad \text{RSS}$$





PERKIN-ELMER COMPUTER CONTROLLED POLISHER (CCP) OPERATION CYCLE

27



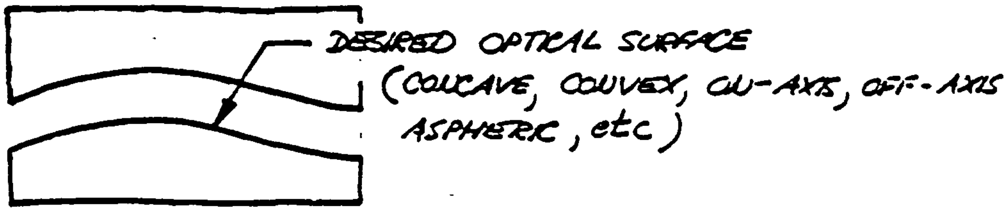
CCP TOOL HEAD

SEMI-REPLICATED SANDWICH MIRRORS

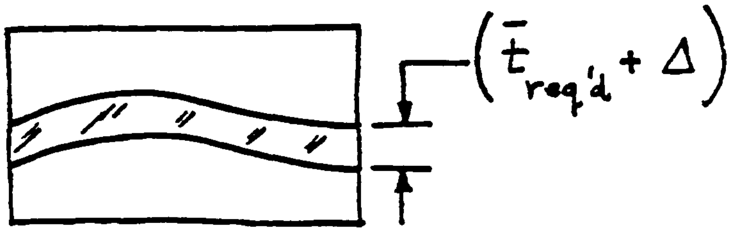
- LARGE ASPHERICITIES CANNOT BE GENERATED ON ULW SANDWICHES ~ TOO FRAGILE.
- MOLDED IN, i.e. SEMI-REPLICATION
- SPHERICALLY GENERATED CORES WON'T "MATCH" THE ASPHERIC FACEPLATE
- UNLESS THE FACEPLATE IS "SPHERIZED"
- THIS CAN BE DONE WHILE THE FACEPLATE IS "RIGIDIZED" ON THE MOLD FORM
- THEN MIRROR IS ASSEMBLED

HOW TO MAKE A "REPLICATED" SANDWICH MIRROR

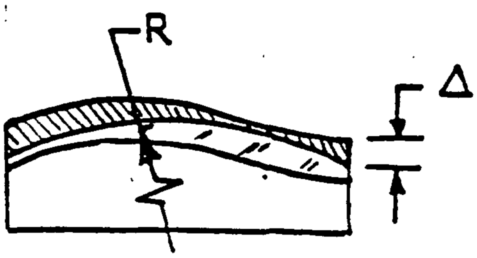
- PRODUCE THE MOLDING FORMS



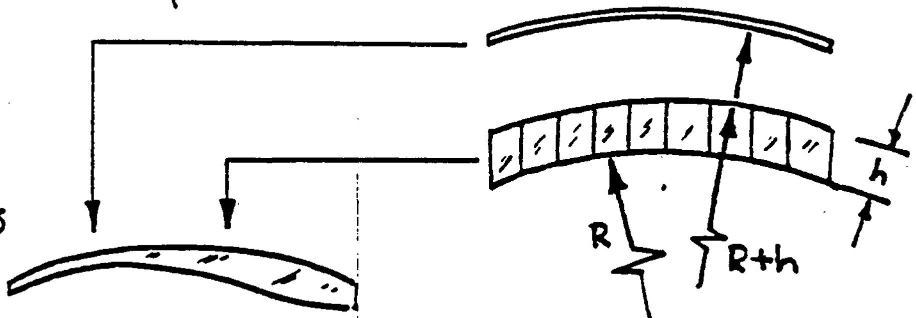
- MOLD THE GLASS



- MACHINE SURFACE TO SPHERICAL (R) CONTOUR

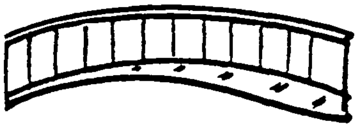


- ASSEMBLE PARTS



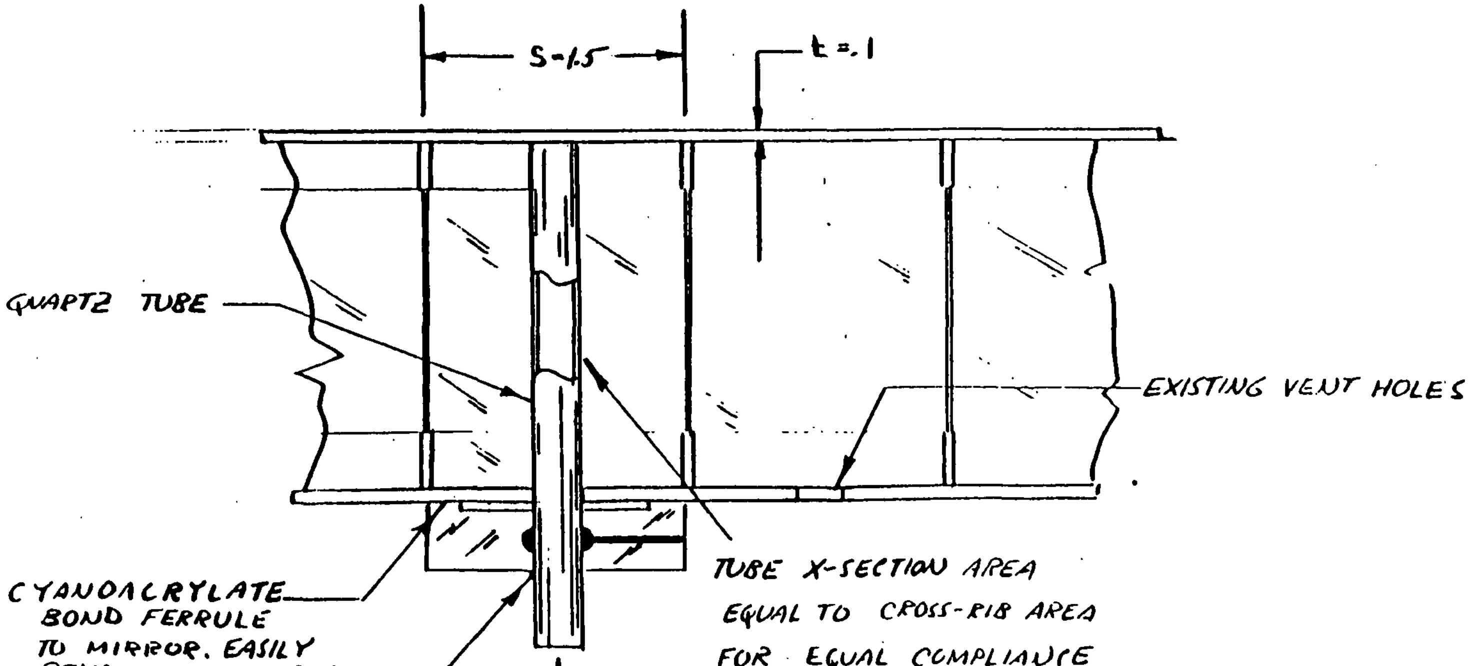
- GENERATE THE CORE & BACKPLATE TO SPHERICAL CONTOURS

- TOUCH-UP & SHINE THE OPTICAL SURFACE



6/29/82

HOW TO AVOID QUILTING SIMPLY



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

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

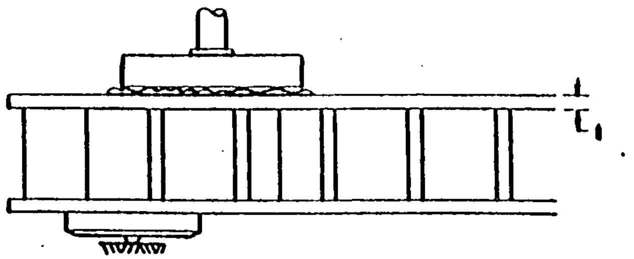
3 • EPOXY BOND FERRULE TO TUBE.

$P = 0^{+.15}_{-0}$ lbs

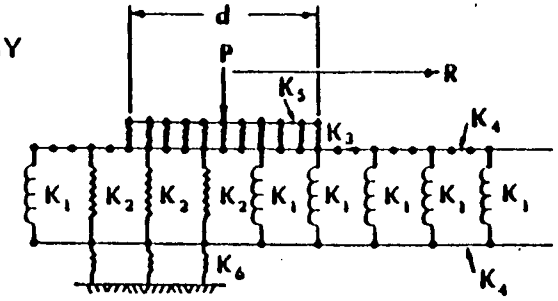
1 • INSTALL TUBE & FERRULE FOR CENTERING

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

- 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



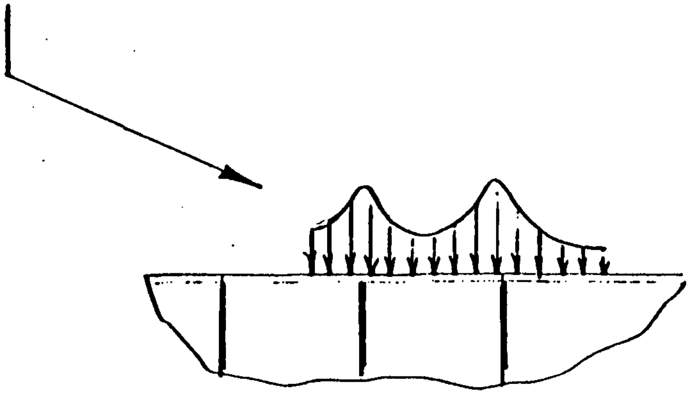
EQUIVALENT PHENOMENOLOGY MODEL



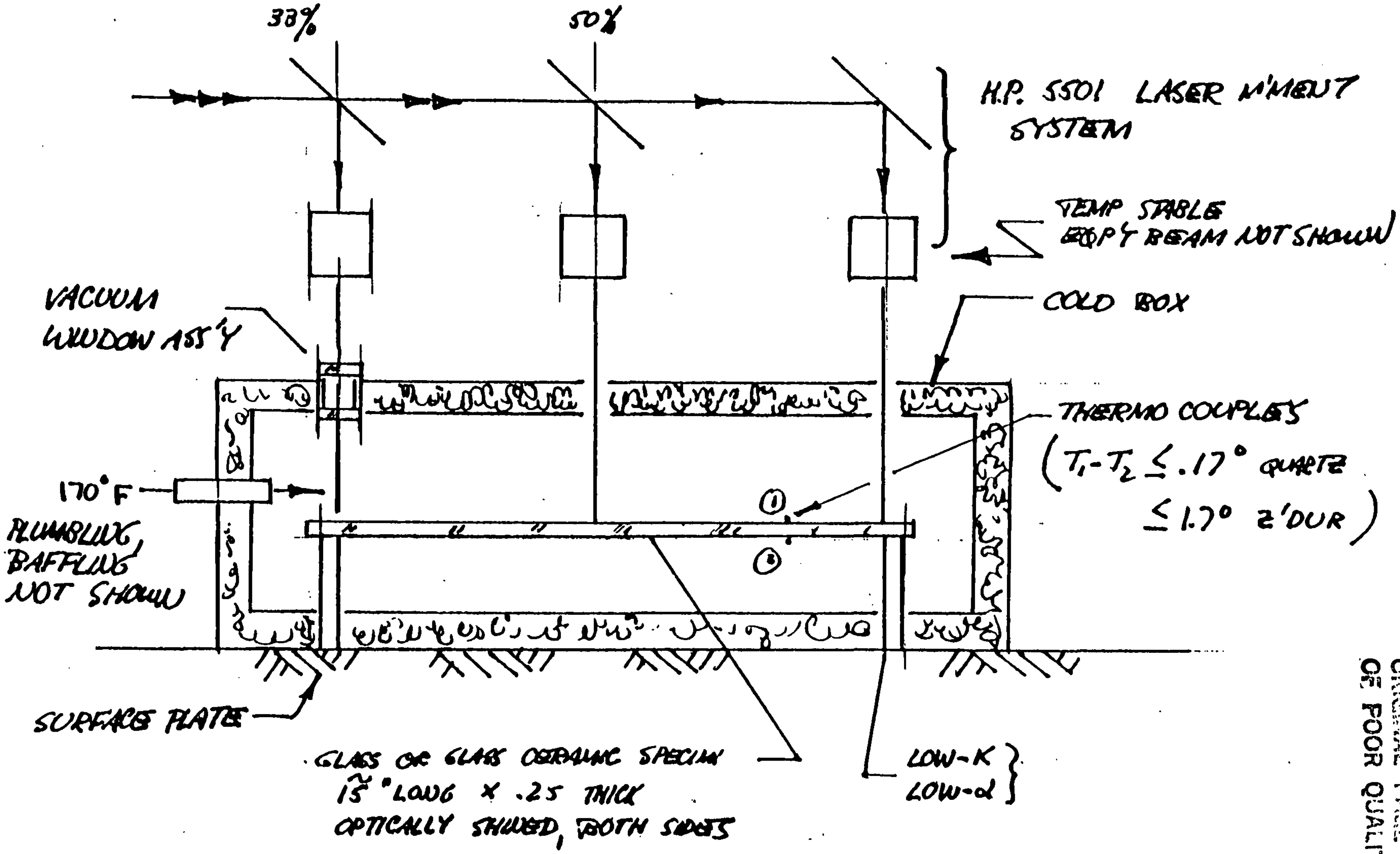
K_1	Core
K_2	Reinforced Core
K_3	Polishing Pad
K_4	Faceplates
K_5	Tool (Very stiff!)
K_6	Support

OUTPUT: Force in springs K_3 as a function of K_1, K_2, K_4 and position of pad along direction R.

Figure 3



SIMPLIFIED SKETCH OF TOOL PRESSURE VARIATION / QUILTING MODEL



APPARATUS FOR THRU-THE-THICKNESS CTE M'MENTS

TECHNOLOGY
DEVELOPMENT PLAN

TECHNOLOGY DEVELOPMENT PLAN

- PRODUCE A 40" Ø <u>HERAEUS</u> MIRROR @ 15 Kg/m^2 TO $\frac{\lambda}{40}$ @

  INCLUDING THE:
    OPTICAL STYLUS
    QUILTING POST
    GRAPHITE DIES
    etc

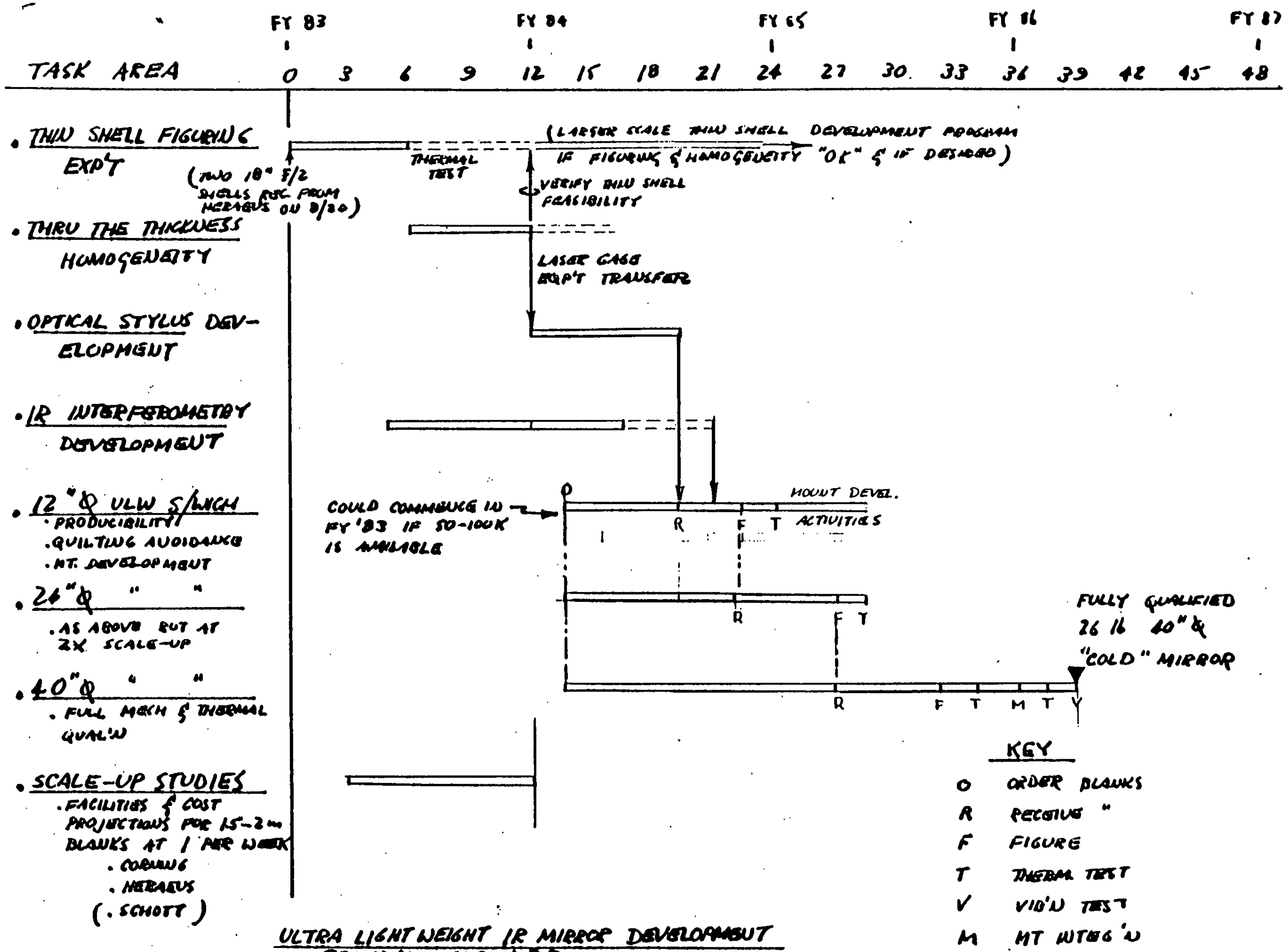
  AND CONDUCT SCALE-UP FACILITIES IMPACT STUDY

- LOW LEVEL FUNDING TO <u>CORNING</u> FOR DEVELOPMENT

  OF A DOMESTIC BLANK SOURCE

    .PYREX ULW
    .TGC

SCHEDULE



ULTRA LIGHTWEIGHT IR MIRROR DEVELOPMENT PROGRAM FOR LDR

IDENTIFY AND EVALUATE PRIME TECHNOLOGIES

5

IDENTIFY & EVALUATE PRIME TECHNOLOGIES

- FUSED QUARTZ

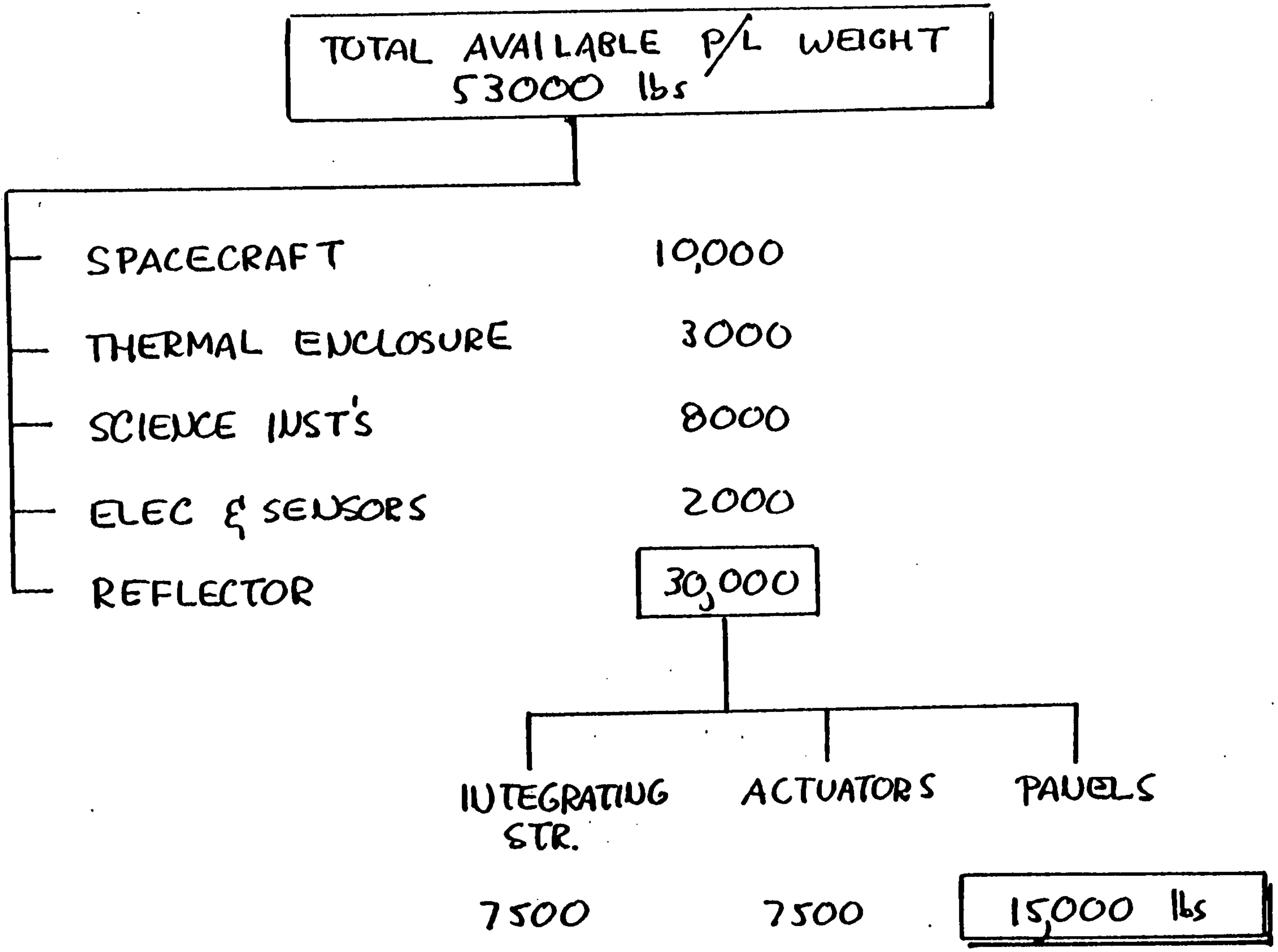
  VIRTUALLY GUARANTEED PERFORMANCE ....

  IF WE CAN MAKE IT LIGHT ENOUGH

- AND IF ITS LIGHT ENOUGH

  CAN WE MAKE IT ?

- WEIGHT DRIVEN CONFIGURATIONS & PRODUCIBILITY



TOTAL AVAILABLE P/L WEIGHT
53000 lbs

SPACECRAFT	10,000
THERMAL ENCLOSURE	3000
SCIENCE INST'S	8000
ELEC & SENSORS	2000
REFLECTOR	30,000

INTEGRATING STR.	ACTUATORS	PANELS
7500	7500	15,000 lbs

WEIGHT BUDGET, NOT MUCH AVAILABLE
FOR 20+ m LDR's

DIAMETER	AREAL DENSITY	EQUIV. SOLID THICKNESS	
10 m	87 Kg/m^2	1.6 inches	
15	39	.7	
20	22	.4	LDR "TERRITORY"
25	14	.25	
30	10	.18	

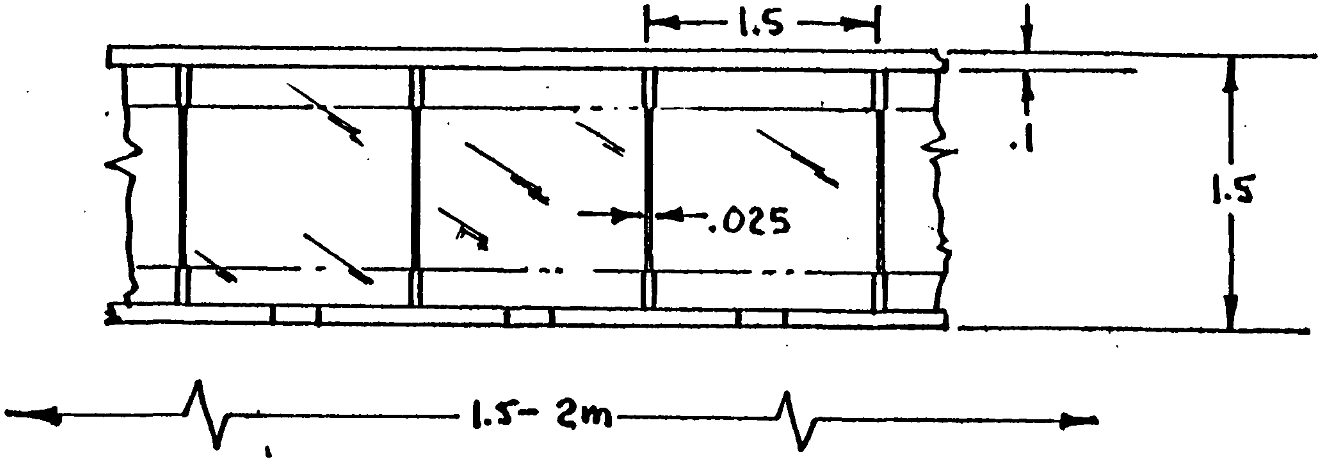
EQUIVALENT "SOLID" GLASS THICKNESS for 15,000 lbs

15 Kg/m^2 IS NEW TECHNOLOGY FOR $1\frac{1}{2}$ – 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. "SANDWICHES"
THRU-THE-THICKNESS CTE VARIABILITY	CRITICAL, 2×10^{-10} $\Delta\alpha$'	LESS CRITICAL, 1.5×10^{-9} $\Delta\alpha$ FACEPLATES
FIRST MODE $\geq$ 10 cps	1-1.5 m⌀ LIMIT	2-m⌀ OK
STRESS, MOUNTING	~.75-m⌀ LIMIT @ 10g UNLESS "SPECIAL" MTG PROVISIONS MADE	2-m⌀ OK
SELF WT. DEFL'N	1800 λ	~72 @ 2μ @ 2-m⌀
PRODUCIBILITY		
BLANK MANUFACTURE	$\boxed{\text{SIMPLE, "CHEAP"}}$	ADVANCED TECHNIQUES, $'s
FIGURING	".... SEVERAL INVENTIONS REQ'D"	
QUILTING or speed-up	~	THE "QUILTING POST" INVENTION

MATERIAL SELECTION IMPLICATIONS

- **SOLIDS** $\Delta(\alpha') \leq 2\times10^{-10}/°F$

HERAEUS QUARTZ ^{*_1}	.13%	HOMOGENEITY, ISOTROPY	OK
SCHOTT ZERODUR	.7%	" "	OK
CORNING "CANDIDATE")	???		

- **SAUDWICHES** $\Delta(\bar{\alpha}) \leq 1.5\times10^{-9}/°F$

HERAEUS QUARTZ	1%	FACEPLATE MATCHING	OK
ZERODUR ^{*_2}	6%		
I-70 HIP BERYLLIUM	.03%	HOMOGENEITY (???) re $\Delta R/R$	

$*_2$ ALSO FRIT DEVEL. ISSUES

$*_1$ OPTOSIL-III

SOLID QUARTZ REFLECTOR PANELS

(20m f/1 BASELINE EXAMPLES SHOWN)

PANEL SIZE	AREAL DENSITY (Kg/m²)						
	8	10	12	14	16	18	20
1-m	10	12.8	15.6	17.7	19.9	22.7	26
1.5m	4.4	5.7	7	7.9	8.9	10	11.4
2-m	2.5	3.2	3.9	4.4	5	5.7	6.4
	FIRST RESONANCE (cps)						
THICKNESS	.14	.18	.22	.25	.28	.32	.36

- FAMILY OF THIN SOLIDS CAN MEET LDR FREQ REQ'TS
- VIABILITY OF DESIGN DEPENDENT ON:
  a) THRU-THE-THICKNESS CTE GRADIENT REPEATIBILITY
  b) ELIMINATION OF SECONDARY OR REDUNDANT MOUNT CONSTRAINTS
  c) ABILITY TO FIGURE THIN SHELLS IN STRAIN-FREE CONDITION

A MORE CONSERVATIVE APPROACH

- a), b), & c) CRITICALLITY DIMINISHED IF ....
- SANDWICH MIRRORS COULD BE BUILT AND POLISHED
- FOR THE SAME AREAL DENSITY.

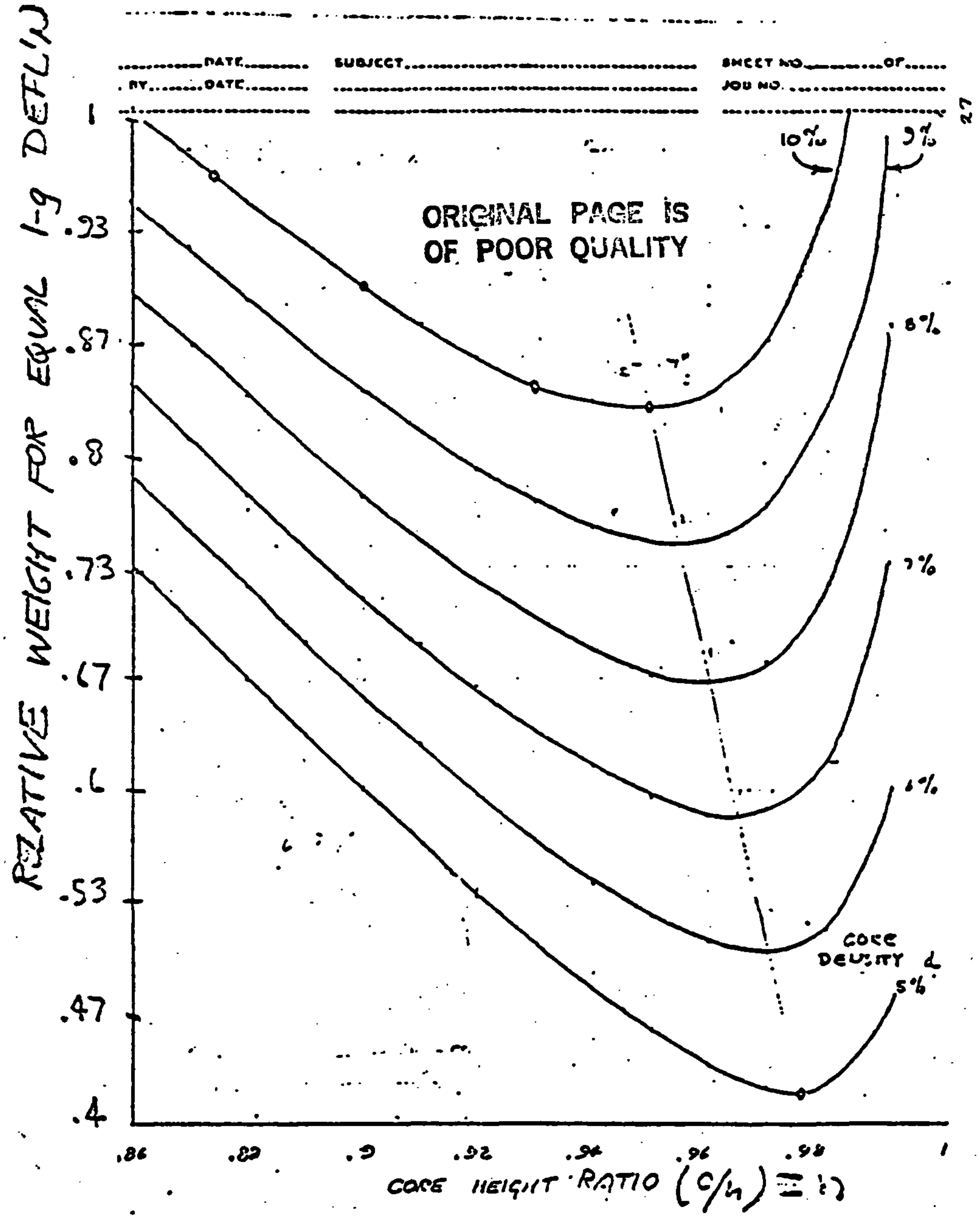
WE BELIEVE THEY CAN !

RADIAL & TANGENTIAL SAGITTAL DIFFERENCES (Δ SAG) for PANELS IN THE OUTERMOST RING

DIA (m)	F/No	R (m)	R_1 (m)	SAG_1 (m)	R_2 (m)	SAG_2 (m)	Δ SAG (in)
20	F/1	40	41.11 (41)	.003041 (01219)	43.43 (43.076)	.00288 (.01161)	.0064 (.0231)
20	F/.5	20	22.14 (21.93)	.005646 (.0228)	27.14 (26.37)	.00461 (.01896)	.0409 (.151)
40	F/.5	40	44.50 (44.283)	.002809 (.01129)	55.08 (54.27)	.002269 (.00921)	.0213 (.0818)

NON-BRACKETTED VALUES 1-m PANELS
BRACKETTED " 2-m "

FIGURE 15



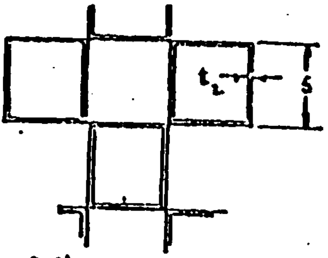
$$W = .229\,\rho D^4 \frac{(1-n+dn)^{1.5}\left[(1-\nu^2)\right]^{.5}}{\left[E(1-n^3)\Delta\right]^{.5}}$$

Δ = SPECIFIED DEFLECTION
n = CORE/OVERALL HEIGHT RATIO
d = " AREAL DENSITY
ρ = MAT'L DENSITY
D - MIRROR DIAMETER

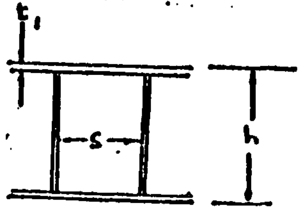
Figure 14

Fig ~~13~~ 14a

Preliminary



$\rho_c = \frac{2st_2}{s^2} = \frac{2t_2}{s}$



$Q = \frac{s^4}{t_1^3}$ & $2000 < Q < 10{,}000$

s	$t_1 @ \rho_c = .03$	t_1 Q = 2000	6000	10,000	OVERALL HEIGHT @ h = $t_1/.015$ Q = 2000	6000	10,000	ρ_A (Kg/m²) Q = 2000	6000	10,000
1.25	.019	.107	.074	.063	4.28	2.96	2.52	18.7	13	11
1.5	.023	.137	.095	.08	5.4	3.3	3.2	23.8	16.6	14
1.75	.026	.167	.116	.098	6.7	4.6	3.9	29.3	20.2	17
2	.03	.2	.139	.117	8	5.56	4.68	35	24.3	20.4
2.25	.034	.234	.163	.137	9.36	6.72	5.48	41	29	24

A 24" 16" 10"Ø
GLASS MIRROR !!
FOR EXAMPLE !!

$\Delta_{1g} = .24\lambda$ P-P @ 23μ

$\sigma_{1g} = 147$ psi

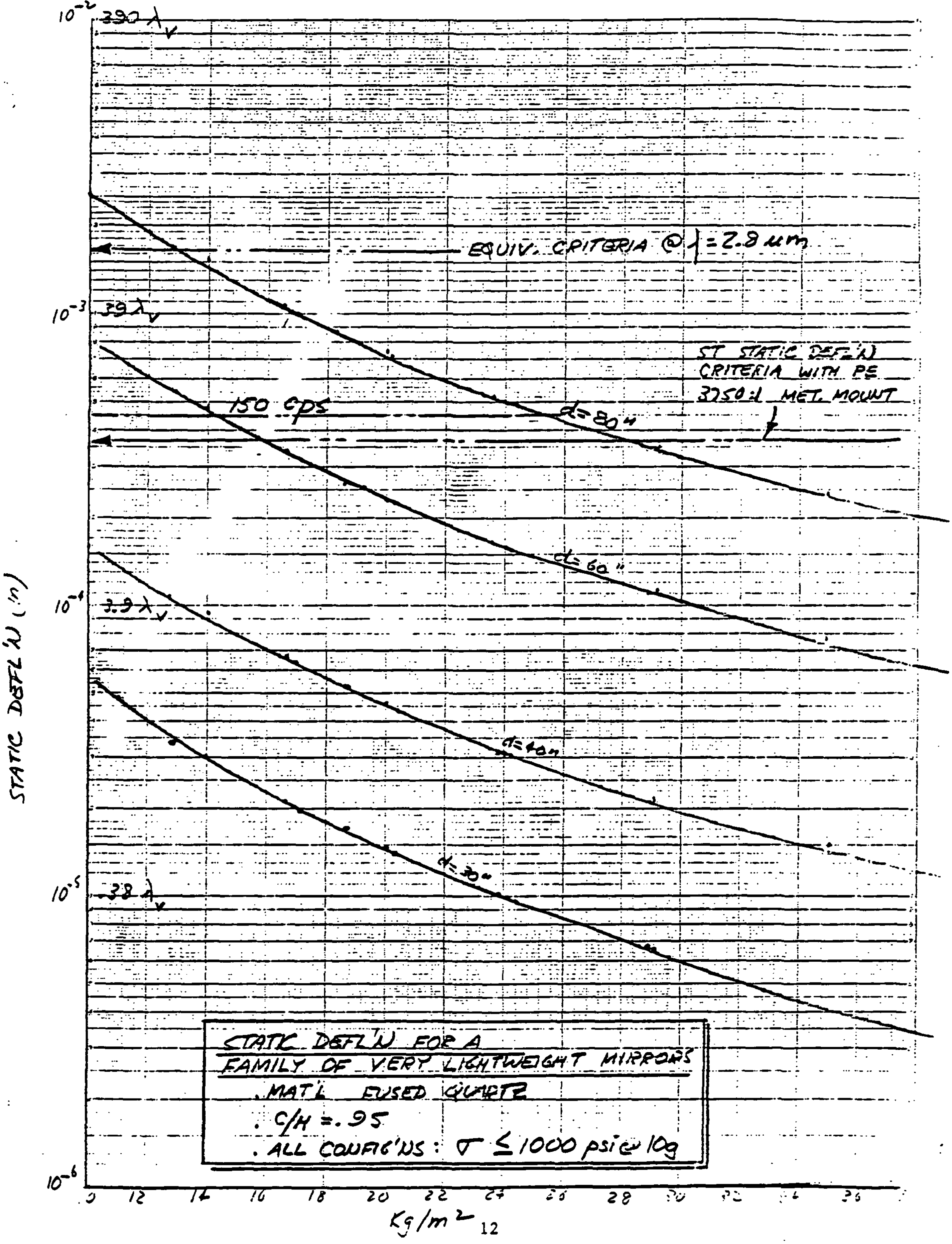
$f = 329$ cps

ALL THIS IS GOOD!!

IN FACT ITS
[illegible] GOOD!!

HERAEUS 3% CORES & PE QUILTING AVOIDANCE
WILL RESULT IN SUPER LITE-WEIGHT MIRRORS

ORIGINAL PAGE IS
OF POOR QUALITY



STATIC DEFL'N FOR A
FAMILY OF VERY LIGHTWEIGHT MIRRORS
. MAT'L FUSED QUARTZ
. C/H = .95
. ALL CONFIG'NS : $\sigma \leq 1000$ psi @ 10g

ORIGINAL PAGE IS
OF POOR QUALITY

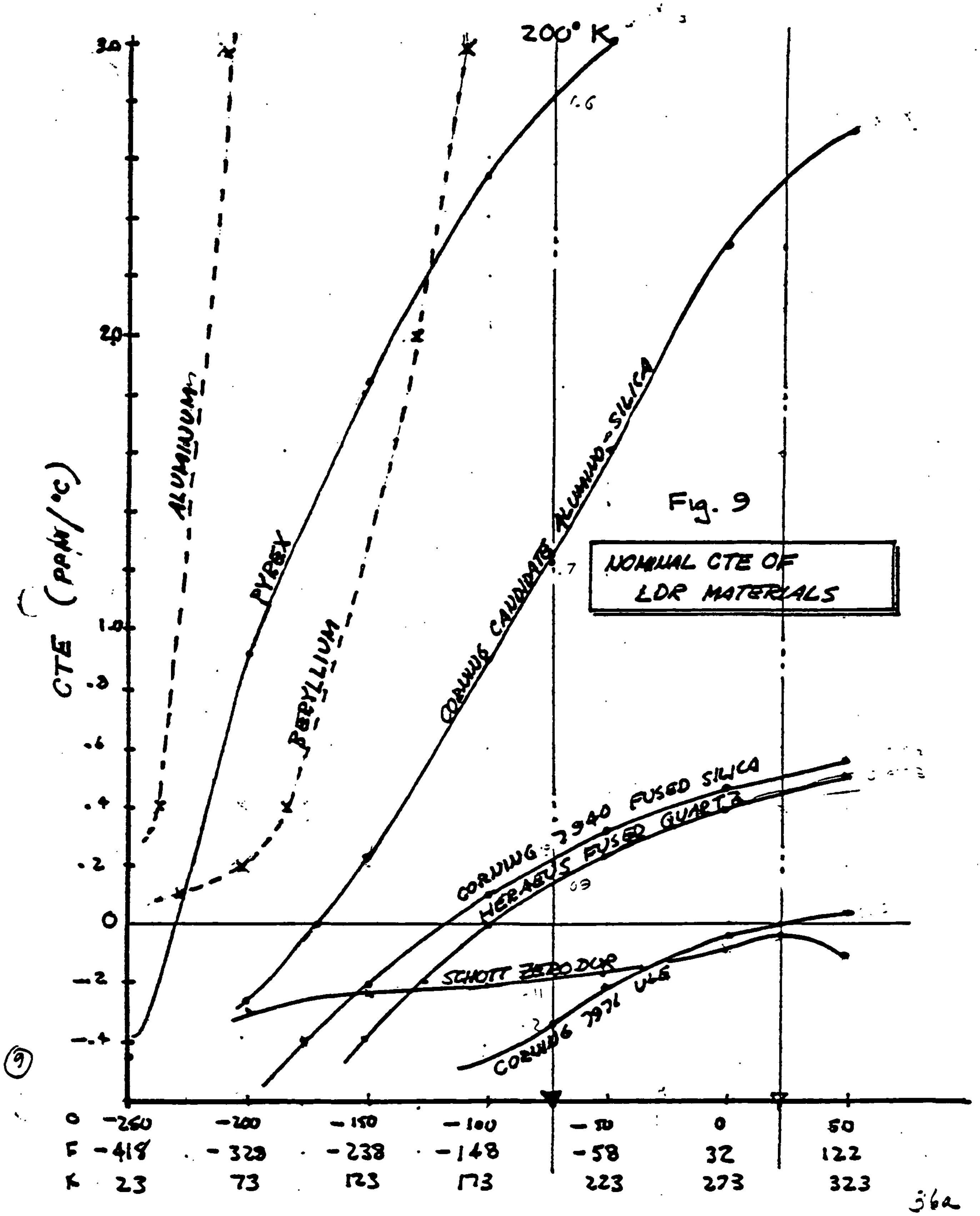
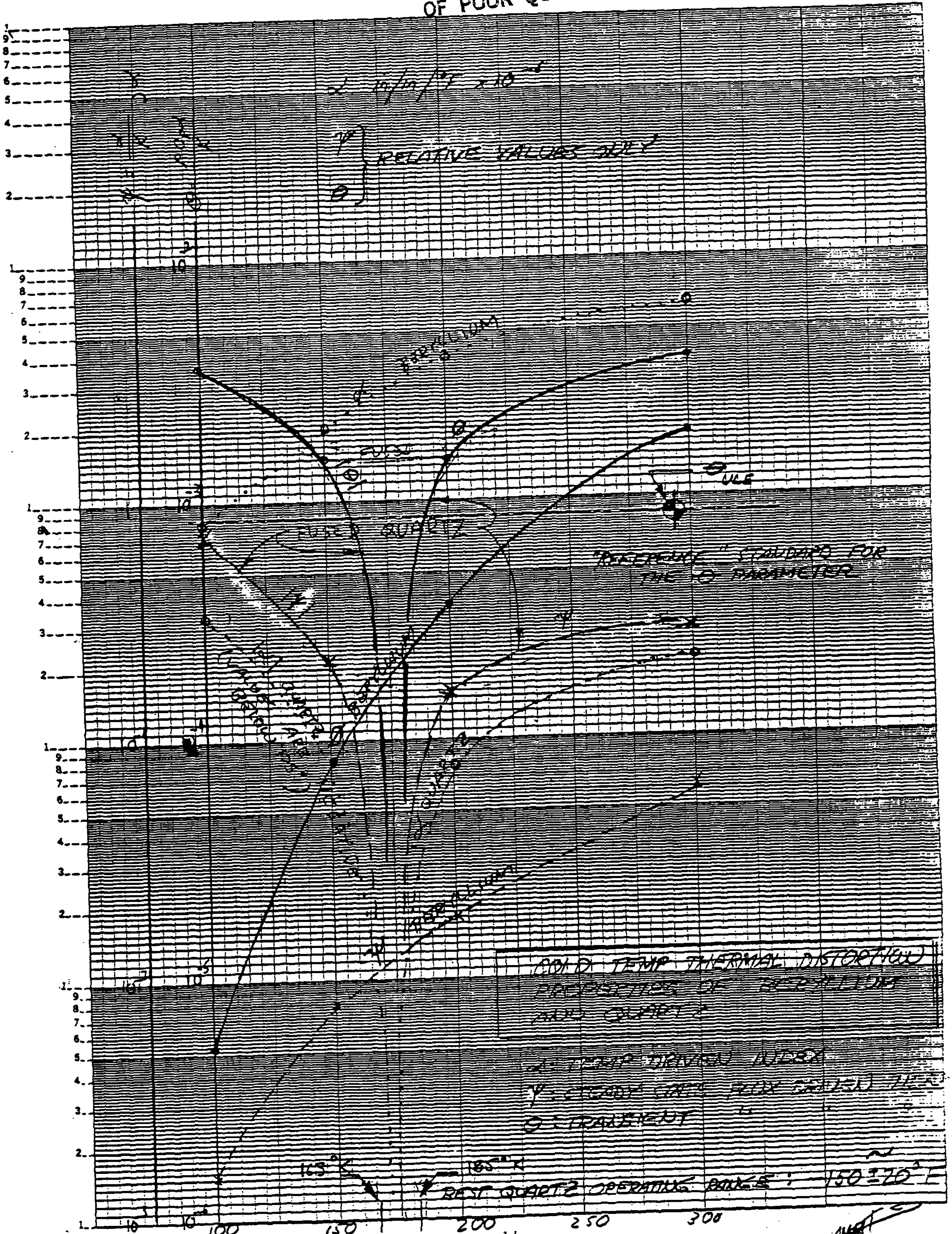


Fig. 9

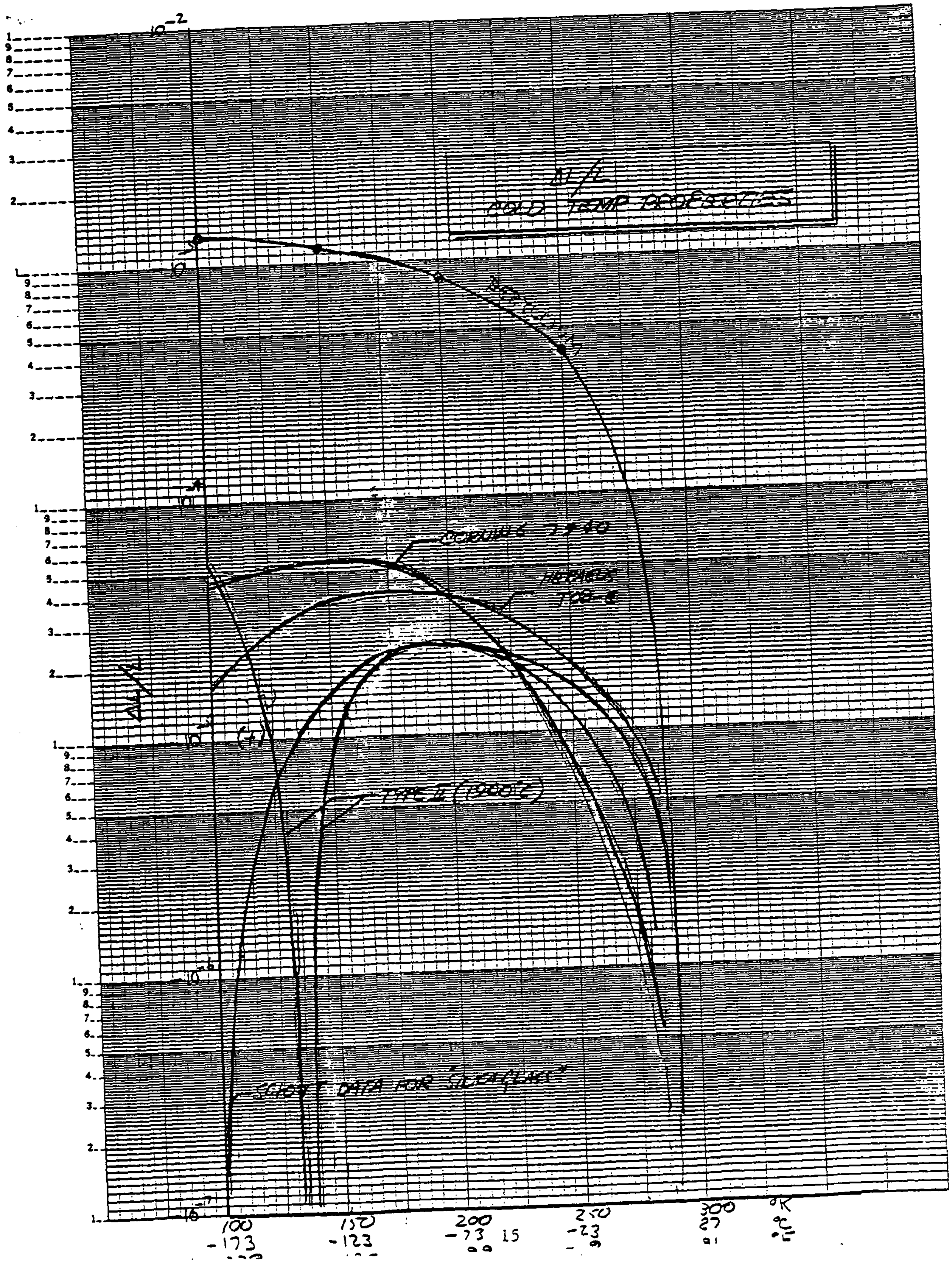
NOMINAL CTE OF LDR MATERIALS

⑨

36a

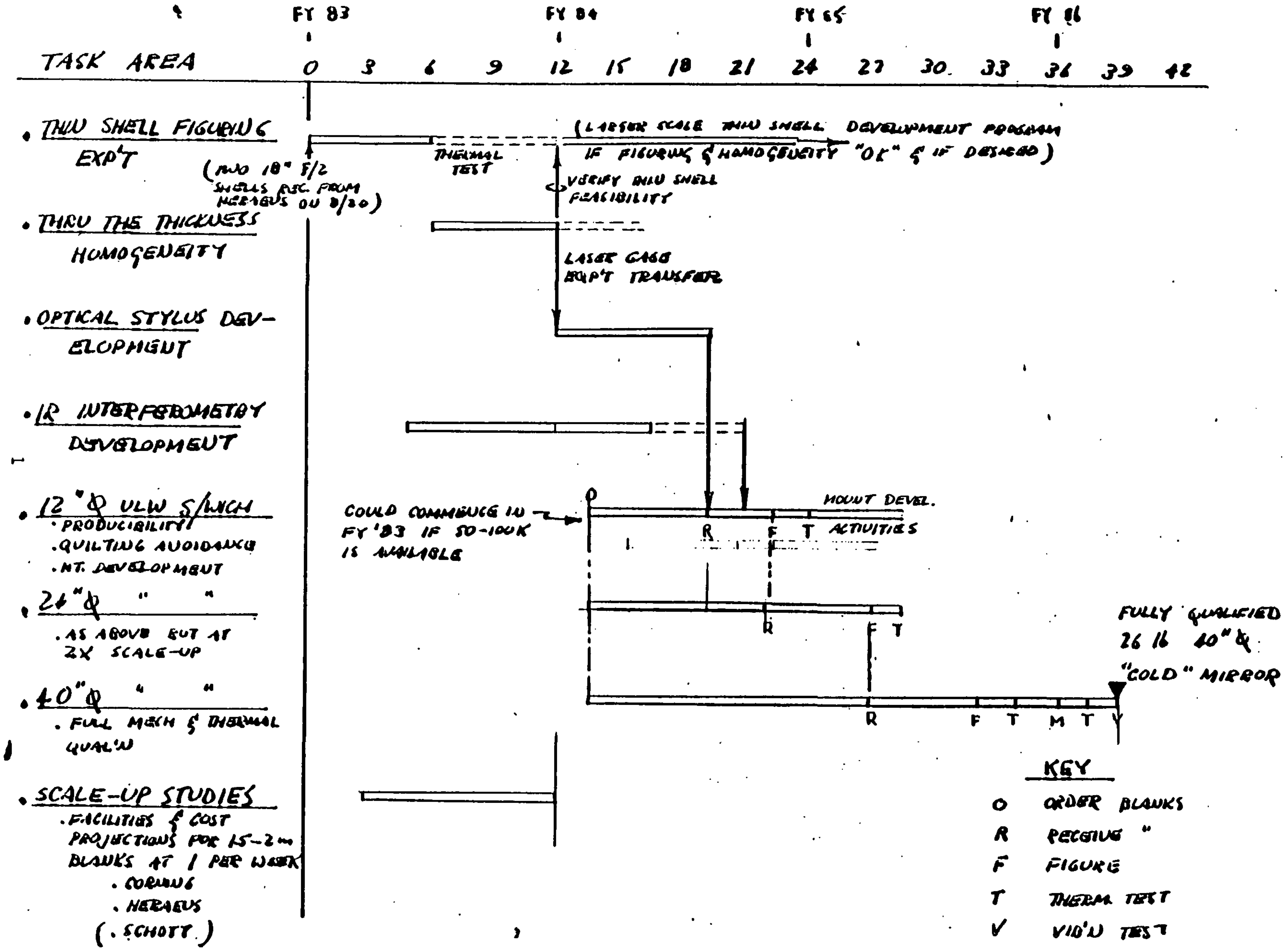


α in/in/°F x10⁻⁶
ψ
θ
RELATIVE VALUES ONLY
BERYLLIUM
FUSED QUARTZ
θ ULE
"REFERENCE" STANDARD FOR THE θ PARAMETER
QUARTZ
BERYLLIUM
COLD TEMP THERMAL DISTORTION PROPERTIES OF BERYLLIUM AND QUARTZ
α : TEMP DRIVEN INDEX
ψ : STEADY STATE FLUX DRIVEN INDEX
θ : TRANSIENT "
165°K
185°K
BEST QUARTZ OPERATING RANGE : ~150 ± 20° F
10
100
150
200
250
300


ΔL/L
COLD TEMP PROPERTIES
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
1
9
8
7
6
5
4
3
2
ΔL/L
(+)
(-)
CORNING 7940
HERAEUS TO8-E
TYPE II (1900°C)
SCHOTT DATA FOR "SILICA"
100
150
200
250
300
°K
-173
-123
-73
-23
27
°C

SCHEDULE

SCHEDULE



KEY
O ORDER BLANKS
R RECEIVE "
F FIGURE
T THERM TEST
V VIB'N TEST
M MT INTEG'N

ULTRA LIGHTWEIGHT IR MIRROR DEVELOPMENT PROGRAM FOR LDR

1. Report No.
NASA CR 166493

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
LDR Segmented Mirror Technology Assessment Study

5. Report Date
March 3, 1983

6. Performing Organization Code

7. Author(s)
M. Krim
J. Russo

8. Performing Organization Report No.

9. Performing Organization Name and Address
Perkin Elmer Corporation
Electro-Optical Division/Optical Technology Division
100 Wooster Heights Road
Danbury, Connecticut 06810

10. Work Unit No.
T-5863

11. Contract or Grant No.
NAS 2 - 11104

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, D.C. 20546

13. Type of Report and Period Covered
CR Final Report

14. Sponsoring Agency Code

15. Supplementary Notes Technical Monitor - Michael K. Kiya
Mailstop 244-15
NASA-Ames Research Center
Moffett Field, CA 94035
(415) 965-6548 or FTS-448-6548

16. 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 presciption of the telescope's primary mirror. To attain diffraction-limited performance, the issues of alignment and/of 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.

17. Key Words (Suggested by Author(s))
Segmented Mirror Fabrication
Alignment System
Large Deployable Reflector Telescope (LDRT)

18. Distribution Statement
Unclassified - Unlimited
STAR Category 89

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of Pages
321

22. Price*

*For sale by the National Technical Information Service, Springfield, Virginia 22161