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Preliminary Design Notes On A Low F-Number EMR

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1 INTRODUCTION

The Electrostatic Membrane Reflector (EMR) is a method of obtaining precisely shaped large concave mirrors of very low weight. It is expected to be most useful in space, where weight is the main limitation on the size of large mirrors.

A thin circular membrane coated with metal is supported at its perimeter. Behind it is an array of electrodes. High voltages applied between the electrodes and the membrane draw the membrane toward the electrodes, forming a concave reflector. A "figure sensor" measures the shape of the membrane; its measurements are used to control the electrode voltages so that the membrane assumes the desired shape and retains it under perturbing forces.

In April 1979[1], design parameters were set forth for an experimental EMR of 4.88 m (16 ft) diameter. It was constructed early in 1980 at NASA Langley Research Center and has been tested on a part-time basis since then. This EMR was intentionally designed to be simple. It provided a check of basic principles and more importantly was used as a demonstration model to gain support and enthusiasm for precision membrane surfaces. Substantial results have been achieved with this model for a very modest investment. Only readily available materials were used in its fabrication.

Lack of funds prevented all but the simplest experimentation and measurement of the EMR shape. The engineering effort expended to design, build, and test the model amounted to about two-thirds of a man-year for GRC and a similar level for NASA Langley. Most of the funds have gone to the purchase of equipment, e.g., precision power supplies, theodolites for measuring surface quality, a microcomputer, and a number of vacuum-coated membranes.

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[1]D. J. Mihora, P. J. Redmond, R. F. Crawford, and M. S. Mortz, Electrostatically Formed Antennas (Test Concept), NASA-CR-159068, General Research Corporation, April 1979.

Even though the prototype EMR is a promotional and demonstration model, engineering data has been obtained and correlated with theory.[1] Learning how to select, handle, and fabricate the membranes has dominated the time spent on installation and operation of the model. During the process of adjusting and measuring the surface, quantitative correlations have been performed. Test data correlations have been made on reflector stability, static controllability, and the shaping of precision spherical surfaces. Even with these limited correlations, confidence has been acquired that much larger, higher-quality EMRs can be designed and built.

Ground tests introduce some environmental problems that would not exist in space. In particular, the effects of humidity on polymer films were significant. When Kapton and Mylar change length as the humidity changes, the electrode voltages must change. A microcomputer program was developed to aid in the control and shaping of the reflector in the presence of humidity changes. Different membranes and coatings were also used in an attempt to circumvent the effects of humidity.

With a small investment, NASA now has a precision 4.88 m testbed that can be actively shaped to within 1 mm (0.04 in) RMS of an ideal reflector. Because of cost limitations, the demonstration model was limited to the forming of a rather shallow spherical reflector (focal ratio $f_N = 3.5$) from an initially flat membrane. The next step is to configure the 4.88 m aperture closer to the shape of an actual spacecraft reflector. A spherical surface of $f_N = 1.0$ is proposed. This next step will demonstrate numerous traits not present in the first model. The design will also be quite inexpensive since it will use the same rim structure and test equipment obtained for the first configuration.

This report presents the preliminary design that is being used in the final design and fabrication of the new EMR.

[1] D. J. Mihora, Test Progress on the Electrostatic Membrane Reflector, NASA-CR-165792, General Research Corporation, June 1981.

2 DESIGN GOALS

Figure 1 is a simple schematic representation of the membrane reflector and the control electrode surfaces, comparing the current and the proposed EMR. The 1979 design approached the practical limit of electrical field strength and pressure exerted on the membrane. Because of humidity, it became difficult at times to set the electrode voltages high enough to form the $f_N = 3.5$ spherical surface. Tests over the last few years have validated previous predictions that $f_N = 3.5$ is a practical limit (even without the effects of humidity) when using a flat Kapton or Mylar membrane. Achieving lower f_N requires preforming. The required electrostatic pressure and therefore the strain is a function of the preformed shape. As the preformed shape is chosen to be closer to the final desired shape, the pressure and strain requirements become smaller. A practical lower limit on strain is introduced by the lowest-mode natural frequency or by wrinkles or irregularities in the membrane. The proposed $f_N = 1$ design can be tensioned to stress levels similar to those in the 1979 design. The same nominal surface quality of 1 mm (0.04 in) is proposed.

With preforming, the deflection of the membrane from its zero-strain position to its design position is much smaller for a given stress. A deflection at the center of 3 mm introduces as much stress as a 90-mm deflection of an initially flat membrane.

The electrode surface proposed for the 1982 configuration is also quite different from the 1979 configuration, as illustrated in Fig. 1. For simplicity, the 1979 electrode surface was a flat plate manufactured from foam and fiberglass. The proposed new electrode surface can be as light as the membrane reflector. It is a thin polymer membrane reinforced with quartz or Kevlar fibers imbedded along the seams. The reinforcement acts as a rip-stop and limits the deflection of the electrode surface.

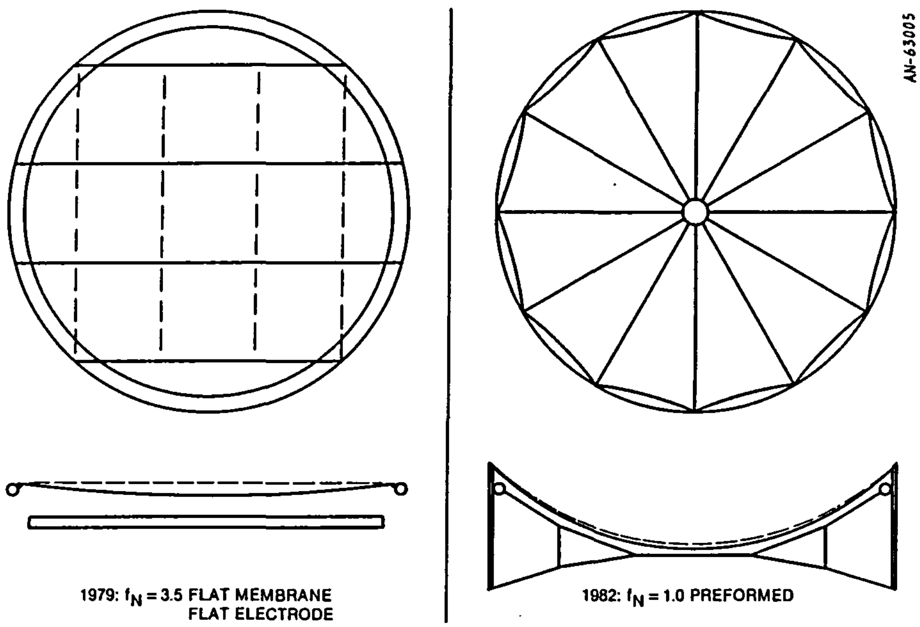

Figure 1. Current and Proposed EMR

Such an electrode surface would be desirable in space because it is both light and packageable.

On the average, the electrode surface is spherical like the membrane reflector. Actually, the surface is formed from 25 flat facets--two rings of twelve and a central facet. Under electrostatic pressure, the facets will belly toward the reflector, but their edges will be held in place by the seam reinforcements.

For the reflector surface, the effects of electrostatic pressure will be much more dramatic than for the old design. The large motion from a highly wrinkled state to the preformed state will be very pronounced. The wedge-shaped flats will become curved. The wrinkles in the membrane will disappear and the scalloped perimeter will become taut.

The proposed reflector has a "catenary" perimeter fixed to the supporting rim at twelve points, instead of being clamped all around as in the old design. There are advantages and disadvantages to this arrangement. Moving the apex of each catenary is an easy and effective way to adjust out the rim errors. However, the catenaries will have to be carefully fabricated. A poor catenary lay-up will introduce wrinkles. The catenary perimeter also adds a degree of freedom not present in the 1979 design. It will be possible to compensate for humidity and temperature with devices such as springs at the mounting points as well as electrostatic control. In this initial design, however, such devices are not included.

High surface quality of the membrane reflector can be maintained despite the varying gap between the two membranes. Low surface quality of the electrode surface is quite acceptable. A detailed analysis was performed to define the geometry of the two membrane surfaces. In the spirit of the 1979 design, simplicity has been a key design goal. The proposed design attempts to minimize the number of electrode flats and drop cords (vertical lines in Fig. 1) while achieving the 1 mm surface quality of the membrane reflector. Design analyses[1] on a 100 m EMR antenna indicate that 4.5 m is a reasonable spacing between drop cords. In scaling to smaller sizes, however, the number of drop cords does not decrease linearly with size. The design analyses indicated that a layout with 12 drop cords would provide the required shaping of the electrode surface.

The loads associated with this new EMR will cause negligible deflections of the rim structure. As a cost-saving measure, the rim structure used with the 1979 design is retained for the new configuration.

[1] D.J. Mihora, R. Chase, M. Mortz, Electrostatic Membrane Reflector Conceptual Designs, General Research Corporation CR-1-1035, p. 45.

Table 1 lists important experiments with the flexible-electrode design. The tests will validate the utility of this precision reflector. Unlike the previous model, this flexible-electrode design is capable of being packaged. It thus contains the essential elements of a spacecraft EMR. This design will be an excellent breadboard for larger, higher-precision reflectors.

TABLE 1

EXPERIMENTS WITH THE FLEXIBLE-ELECTRODE TESTBED

- Validate that the low-mass flexible electrodes will acceptably shape the membrane reflector
- Demonstrate that surface precision is achievable at $f_N = 1$ using commercial membranes
- Explore the benefits of the catenary perimeter
- Identify requirements for perimeter compensation and control
- Evaluate azimuthal and radial electrostatic shape control
- Measure perimeter tensions
- Provide a breadboard for much larger future designs

3 DESIGN NOTES

A low-mass flexible-electrode EMR has been designed as a replacement for the fiberglass/foam design currently being tested at NASA-Langley. The new configuration is designed for a focal-length to aperture-diameter ratio (f_N) of 1.0. This configuration makes maximum use of existing test equipment. The same rim structure, power supplies, and figure sensors as used on the 1979 design are retained.

The preliminary design is the result of roughly two man-months of activity completed between February and May 1982. The design parameters are not optimized but are reasonable values obtained by judgment and familiarity with similar designs.

Only a few limitations constrained the selection of a new design. Primarily, they are the maximum achievable electric field strength (in moist Virginia air) and the membrane reflector's surface quality, which was chosen to be about 1 mm RMS. With very few design alterations, a 0.1 mm surface quality could be achieved. A reflector of this quality would be exceedingly useful as a submillimeter radio telescope. However, unconventional membrane materials and fabrication techniques would be required. A surface quality of 1 mm is satisfactory for most large space-reflector missions, and can be achieved with commercial "off-the-shelf" membranes similar to those used on the prior configuration.

The new configuration will use the same polymer membrane that achieved the best surface quality in prior tests. This was 0.3 mil Kapton with aluminum deposited on both sides. The membrane stress and electrostatic pressure will be lower than in the previous design, but of the same order of magnitude. A deep-dish reflector will be fabricated from flat panels similar to the flat segments of the Lockheed "wrap radial rib" antenna. With adequate electrostatic pressure, the azimuthal flats will assume the required spherical shape. The forming pressure was selected to be 2.6 N/m^2 or about 84 percent of the 1979 design level. The membrane stress is 1.67×10^6 N/m^2 or about 40 percent of the 1979 design level. The design electric field strength of 7.7 kV/cm (19.5 kV/in) is also less than before.

A substantially higher stress, pressure, and field strength could be used if testing were conducted in a vacuum chamber. The EMR would exhibit better quality in such a chamber. The layout of the new design ignored that possibility, however, because of the lack of accessibility and the difficulty of remote operation and testing.

Numerous design options exist for both the membrane reflector and the control electrode surface. For the membrane reflector, the focal length was not prescribed. It was decided to select a value characteristic of a spacecraft radar or radiometer. Trades were performed for focal ratios (f_N) from 0.5 to 1.5, with no special advantage appearing for any particular value. A $f_n = 1.0$ spherical reflector with a radius of curvature of 9.76 m was selected. This focal ratio is typical of a spacecraft antenna.

Most of the design engineering of the new configuration involved the control electrode surface. Our primary goal was to select the simplest electrode layout while demonstrating the attractiveness of the flexible-electrode approach. The electrode surface can be very far from spherical as compared to the reflector surface. Imperfections and irregularities in the electrode surface are not transmitted to the reflector surface. Using this characteristic to advantage, the electrode surface can be formed from flat elements. The flat elements are positioned by drop cords (strings) at each corner of the elements. Figure 2 shows a front view and two sectional views of the electrode surface and reflector.

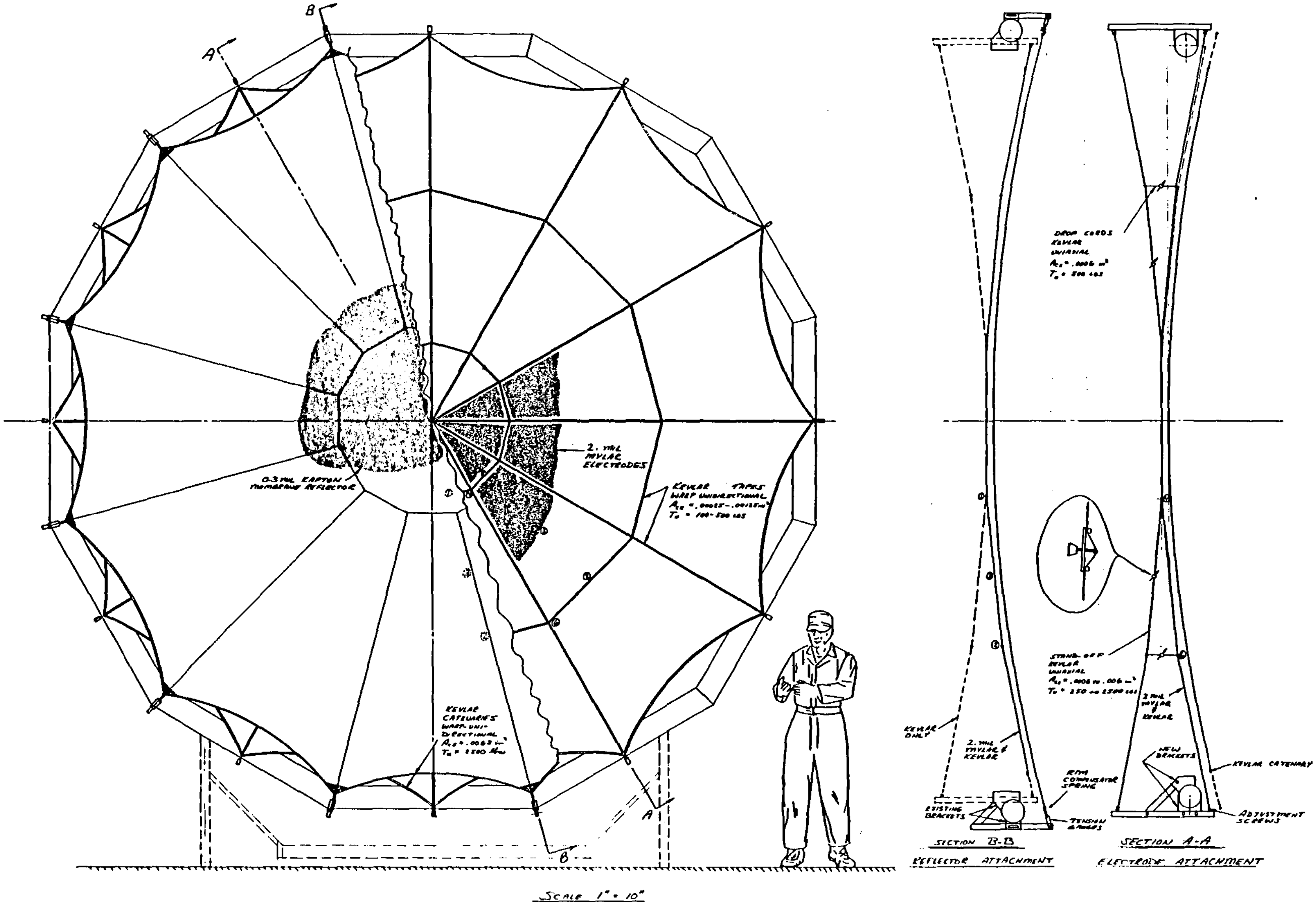

Figure 2. Flexible Electrode EMR--1982 Design
(Modification of the 1979 Testbed)

The electrode surface is shaped using a central flat and two outer rings of flats. The outer flats are trapezoidal gores which provide the necessary concavity. Twelve gores in each ring form the surface. In mirror image to the electrode surface are the Kevlar standoff cords, which form an open "spider web", concave to the rear (left side in Section A-A) of the same shape as the edges of the gores. The membrane reflector, the electrode surface, and the standoff cords are tensioned by the electrostatic force. The rim provides the necessary compression reaction to maintain the entire surface. Thus, there are no rigid structural elements inside the rim. This arrangement provides for a highly packageable antenna.

The front view in Fig. 2 displays the differences in gore geometry between the reflector and the electrode surface. The gores forming the membrane reflector are curved in the radial direction (but flat in the azimuthal direction, since an initially flat membrane can only be curved in one direction). That is, the radial seams of the membrane reflector are curved lines. All the seams of the electrode surface,on the other hand, are straight lines with uniaxial Kevlar fibers bonded along them.

Of necessity, all the Kevlar cords used in the EMR must be uniaxial. Woven tape does not provide the required stiffness under the electrostatic stress. The uniaxial layup is especially important in the catenaries that form the edge of the membrane reflector. Ideally, the catenaries should be inelastic to provide the best attachment constraint. The catenaries can be curved to arc segments. A better but more difficult catenary layup is a segment of an ellipse.

During initial testing of the EMR, it is recommended that the catenaries be attached directly to the rim structure. This "hard mount" allows for direct correlation of experiment with theory. In future tests, interesting results may be achieved by inserting a soft spring between the catenary and the rim.

Figure 3 defines the geometry of the electrode panels. The coordinates and dimensions shown were selected to achieve the simplest layout and best quality. The electrode surface has an average spacing of 5 cm (2 in) from the membrane reflector. The recommended material for use in space is a minimum-gage polymer similar to the membrane reflector. For this model, however, a thicker membrane is proposed: 2 mil Mylar is suggested. Different electrode patterns can be attached to and removed from the 2 mil substrate without danger of tearing it. Figure 4 lays out the patterns for the electrode assembly.

The electrode pattern to be applied to the electrode surface, shown in Fig. 5, is essentially the same layout used with the $f_N = 3.5$ design. Ten separate power supplies control the voltages to the ten segments. Each segment is a conductor material such as minimum-gage aluminum foil. The Mylar is an excellent insulator between the electrodes.

The proposed EMR will be used for much more than a demonstration model. The configuration will be a testbed for various mechanical and control options. The 4.88 m size in "manageable" for many design changes that would not be practicable in a larger model. Figure 6 indicates the scale-up to a 15 m (50 ft) EMR which would incorporate the attributes of the smaller configuration. Although the 4.88 m configuration is adequate to demonstrate the various factors influencing surface quality, the larger configuration is needed to validate the potential of the EMR for larger sizes. The 15 m EMR would use the same materials as the smaller one. It would utilize a very light (but not deployable) rim.

ELECTRODE CO-ORDINATES
(RELATIVE TO REFLECTOR CENTER)

X	Y	Z	L	(TRUE LENGTH)
0	0	– 1.753	—	
5.228	19.5115	– 1.753	20.200	⓪ TO ④
15.634	58.3475	2.2098	40.401	④ TO ⑥
25.88	96.5865	10.097	40.466	⑥ TO ⑦

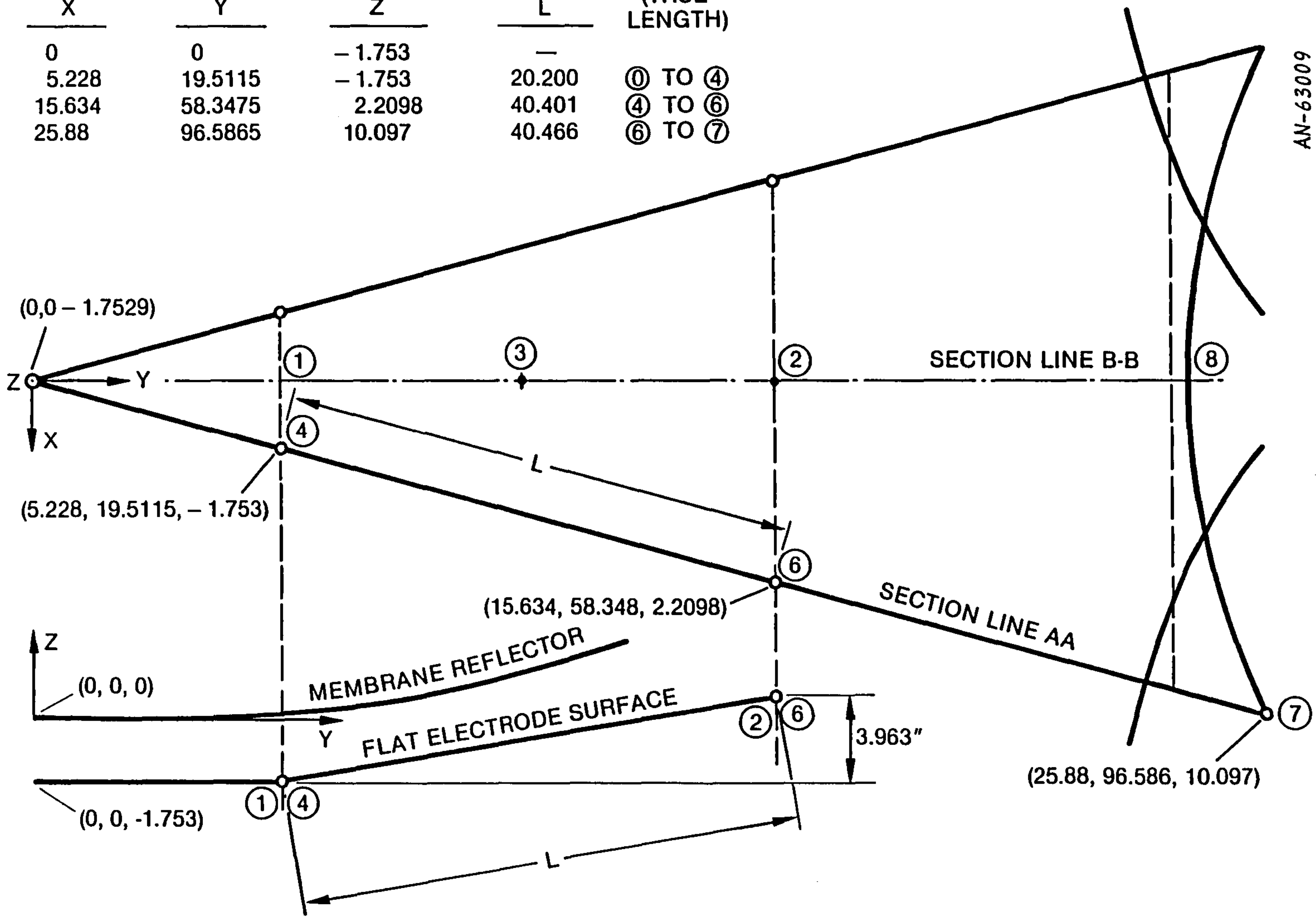

Figure 3. Electrode Coordinates (inches) Relative to Reflector Center

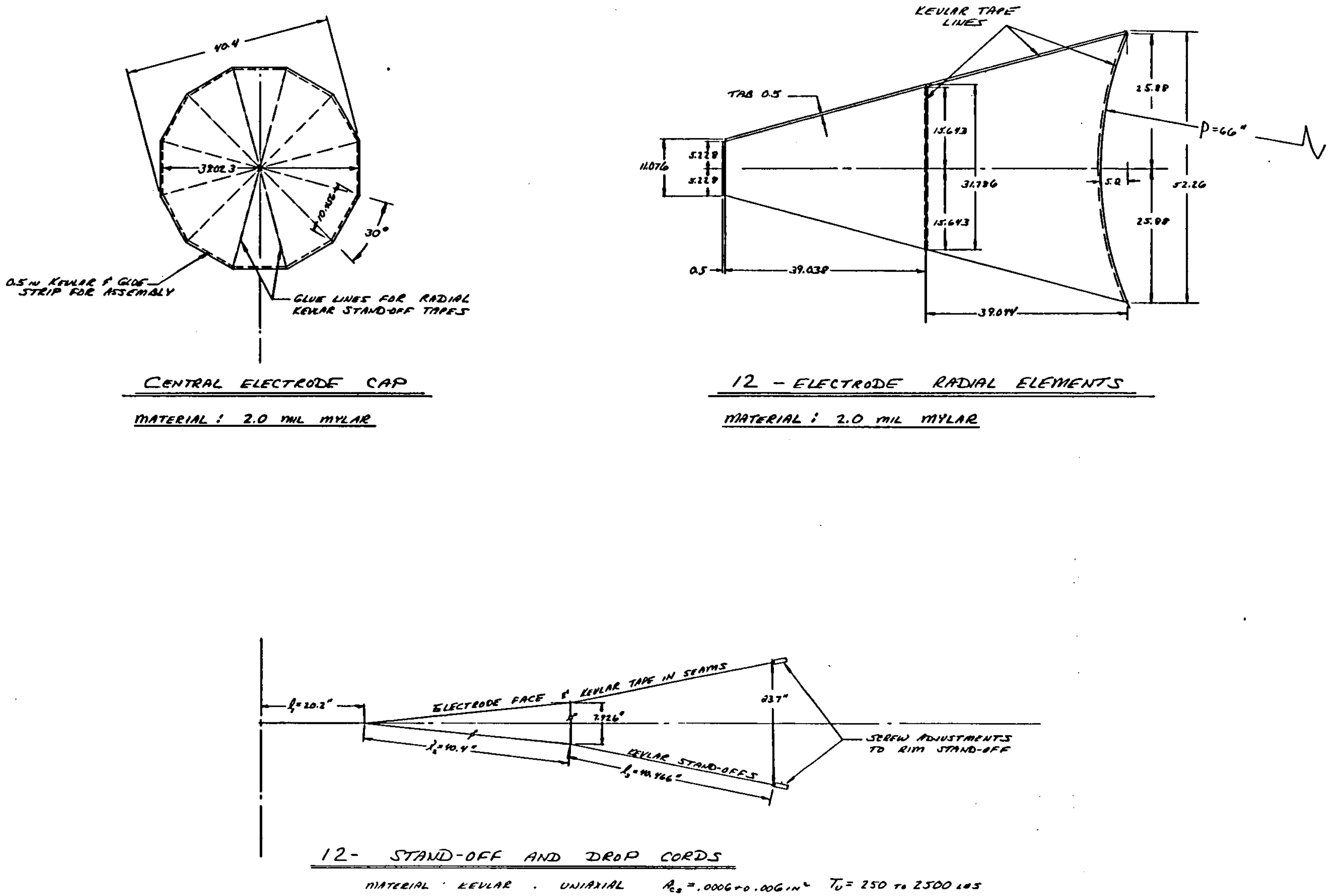

Figure 4. Patterns for Electrode Surface and Standoff Tapes

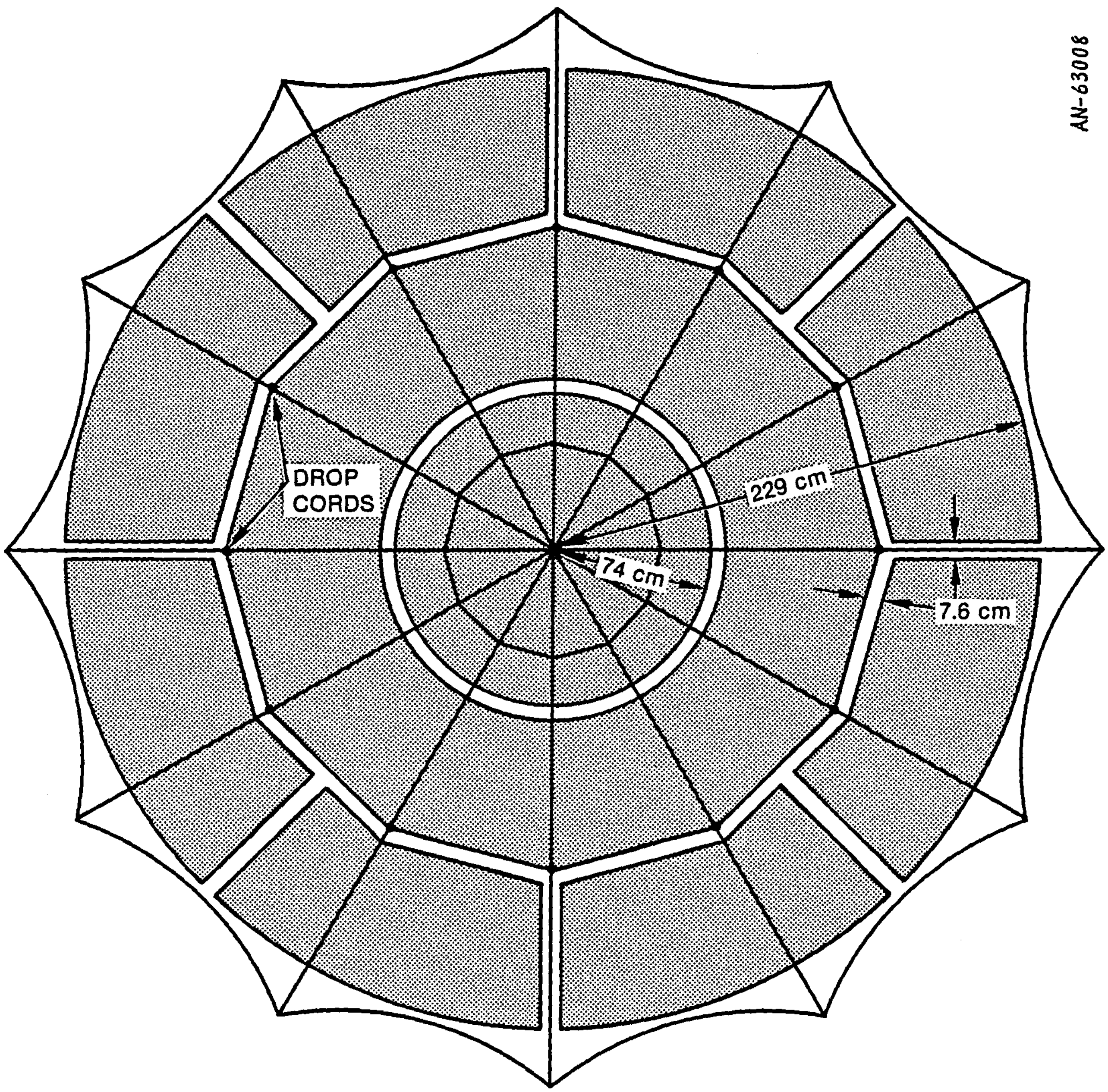

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Figure 5. Electrode Segmentation

1	LIGHTWEIGHT NON-COLLAPSIBLE E-GLASS RIM
2	KEVLAR STAND-OFF TAPES
3	KEVLAR DROP CORDS
4	FARADAY ENCL. (OPTIONAL)
5	ELECTRODE SURFACE
6	PRECISION EMR
7	HIGH VOLTAGE POWER SUPPLY--CRT TYPE
8	LOW VOLTAGE (0-20V) CONTROL LINES
9	HP-85 CONTROLLER

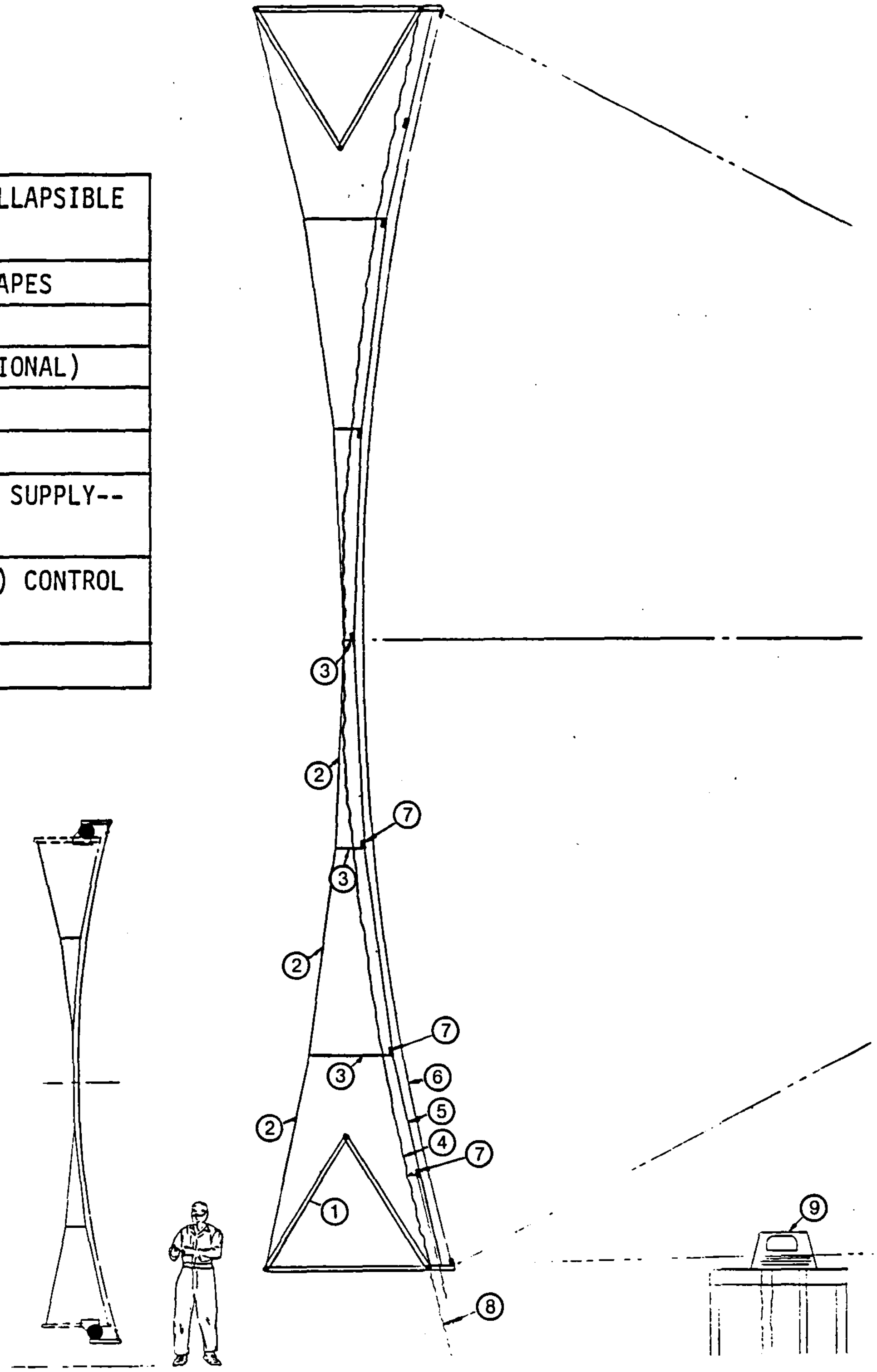


Figure 6. Proposed Scale-Up of EMR

Table 2 summarizes the materials recommended for the proposed EMR—the fiber reinforcements and the membrane materials. A wide range is shown in the size of the standoff fibers. The larger size shown provides an extra stiff support, with which the electrode surface deflects about 0.3 mm. The smaller size results in a 3 mm electode deflection, which is also quite acceptable. Only for the catenaries is the minimum fiber strength (or stiffness) critical. The 12-point attachment necessitates a stiff catenary to properly transfer the entire membrane loading along the perimeter without wrinkles.

The important parameters of the proposed EMR are summarized in Table 3. As mentioned previously, operation in sea-level conditions influenced the selection of the pressures and geometry. The membrane variables are listed as a function of radius in Table 4.

This preliminary design activity has defined the basic parameters. The subsequent design details to be performed at NASA, Langley, will address the finer details associated with fabrication. The test program will provide important information and refinements of the design. There are several open issues that the testing will better expose.

Probably the most challenging upcoming task is the fabrication of the catenaries and the seams in the membrane reflector. The catenaries shown in Figs. 2 and 3 are not the optimum geometry but a reasonable first design. They are circular arcs with a width-to-depth ratio of 10 to 1, and provide a reasonable boundary condition provided the catenary material is inelastic. More exotic catenary shapes and attachment techniques are contemplated. In the near future, a compensating device will be attached between the catenaries and rim. The device may be able to compensate for thermal and hygroscopic expansions of the reflector. The spring constant and location of the compensator, and electrostatic control along the perimeter, combine to achieve successful compensation.

TABLE 2

MATERIALS SUMMARY

Fibers	Material	Layup	Cross Section Area (in^2)	Ultimate Strength (lbs)
Standoff	Kevlar or Graphite	Uniaxial	6.3×10^{-4} to 6.3×10^{-3}	250 to 2500
Drop Cords	Kevlar or Quartz	Uniaxial	6.3×10^{-4}	250
Electrode Seam Reinforcement	Kevlar	Warp Unidirectional or Longitudinal "G"	1.25×10^{-3}	500
Catenaries	Kevlar or Graphite	Uniaxial	6.3×10^{-3}	2500

Membranes	Material	Thickness (mils)	Aluminum Conductor
Reflector	Kapton	≤0.3	500 to 1000A on both sides
Electrode (Spacecraft)	Kapton	≤0.3	1000A
(Model)	Mylar	2.0	0.1 mil aluminum foil electrodes

TABLE 3

PARAMETER SUMMARY

h = 7.5 μm (0.3 mil) Membrane reflector is Kapton with a vacuum deposited coating of aluminum of 1000A.

E_Y = 5.5×10^9 N/m^2 (800,000 psi) Modulus of elasticity as derived from prior tests.

ρ_f = 9.76 m (32.021 ft) Formed radius of curvature with application of the electrostatic pressure.

ρ_o = 9.8559 m (32.335 ft) Manufactured average radius of curvature.

$\Delta Z(0)$ = 3.1 mm (0.122 in) Deflection of membrane centerline with load application.

$\overline{GAP}$ = 50.8 mm (2.0 in) Average spacing between electrode surface and membrane reflector.

$\frac{\overline{GAP}}{\Delta Z} \geq$ 16.3 A high degree of position stability for values greater than 2.0.

P = 2.615 N/m^2 Peak centerline electostatic pressure.

E_E = 769 kV/m (19.5 kV/in) Maximum electrostatic pressure.

$\sigma(0)$ = 1.67×10^6 N/m^2 (240 psi) This maximum membrane stress at the center is adequate to eliminate wrinkles but not enough to introduce creep or Griffith crack propagation problems.

$\Delta P/P$ = 0.4 Spatial variation of electrostatic pressure caused by the varying gap between the membrane reflector and the electrode panels. A periodic 2.5 cycle radial variation combined with a 12-cycle azimuthal variation introduces a surface waviness of about 0.75 mm (RMS).

TABLE 4

SUMMARY OF THE MECHANICAL PROPERTIES OF THE $f_N = 1$ EMR

Radius of curvature = 9.76 m (under tension)
9.855 m (as formed)
Focal ratio = 1.0
Average membrane-to-electrode gap = 5.08 cm

Normalized Radius*	Electrostatic, Pressure, N/m²	Depth behind rim, m Final	Initial	Normalized membrane stress† Radial (NR)	Azimuthal (NTH)	NTH/NR	Electric field, V/m
0	2.61545	.30992	.30681	.02436	.02436	1.00000	769238
1	2.61407	.30943	.30633	.02435	.02434	.99946	769035
2	2.60795	.30797	.30488	.02433	.02425	.99678	768134
3	2.59768	.30553	.30248	.02428	.02410	.99261	766620
4	2.58327	.30211	.29908	.02422	.02390	.98678	764490
5	2.56470	.29771	.29473	.02413	.02363	.97925	761739
6	2.54197	.29234	.28940	.02403	.02331	.96999	758355
7	2.51503	.28598	.28311	.02391	.02293	.95894	754326
8	2.48386	.27864	.27584	.02377	.02249	.94606	749637
9	2.44841	.27031	.26760	.02361	.02199	.93128	744268
10	2.40863	.26100	.25838	.02343	.02143	.91451	73198
11	2.36449	.25069	.24818	.02323	.02081	.89568	731402
12	2.31591	.23939	.23700	.02301	.02013	.87467	723850
13	2.26284	.22710	.22482	.02276	.01938	.85135	715508
14	2.20520	.21380	.21166	.02250	.01857	.82559	706336
15	2.14292	.19950	.19750	.02221	.01770	.79721	696291
16	2.07592	.18418	.18234	.02189	.01677	.76601	685319
17	2.00410	.16785	.16618	.02155	.01577	.73176	673360
18	1.92737	.15051	.14900	.02119	.01471	.69417	660344
19	1.84562	.13213	.13082	.02080	.01358	.65293	646188
20	1.75874	.11273	.11160	.02038	.01238	.60763	630795
21	1.66660	.09229	.01993	.01111	.55781	.55781	614049
22	1.56908	.07009	.01945	.00978	.50291	.50291	595812
23	1.46602	.04826	.04778	.01893	.00837	.44223	575915
24	1.35730	.02466	.02442	.01839	.00689	.37494	554147
25	1.24273	0.00000	.00000	.01780	.00534	.30000	530244

*25 radial stations at 9.76 cm spacing

†Normalized to yield stress of 6.895×10^7 N/m² (10,000 psi)

Ten separate power supplies will be used for the first time with the f_N = 1 aperture. Azimuthal control along the perimeter will use 8 of the 10 power supplies. These perimeter electrodes can be very effective in conjunction with the compensator springs attached to the catenaries. Optimum shape control using 10 independent controllers will necessitate the use of the HP microcomputer to calculate the right combination of voltages. The preferred control algorithm for the 10 electrodes will evolve from the assessment of the control program currently being used with the f_N = 3.5 EMR.

APPENDIX

TRADEOFF CONSIDERATIONS

This appendix describes several important design trades that led to the new baseline configuration. The geometry of the electrode surface was obtained as a result of several design trades. It will be seen that many options exist. The preferred design emphasized simplicity of layout, using a minimal number of drop cords.

The need for preforming the membrane reflector and electrode surface was not an option. A flat membrane reflector cannot be stressed to low f_N by electrostatic pressure alone. Some of the curvature must be built in. For $f_N = 0.5$ to 1.5, most of the curvature is achieved by preforming. Figure A.1 shows the central deflection ΔZ (i.e., the final shape minus the preformed shape) caused by a fixed electric field strength E_E of 800 kV/m (20 kV/in) as a function of focal ratio f_N. The curve is calculated from

$$\Delta Z = \frac{CP\rho^2 (1 - \nu)}{Eh}$$

where
- P = electrostatic pressure
- ρ = final radius of curvature
- ν = Poisson's ratio
- E = Young's modulus of elasticity
- h = membrane thickness

The assumed electric field strength is near the maximum in humid air. For a fixed f_N and a larger aperture and radius of curvature, there will be a larger central deflection. A tenfold growth in aperture (to 48.8 m) will yield a 100-fold increase in central deflection, from 3 mm to 0.3 m for $f_N = 1.0$. The central deflection of an initially flat membrane is shown as a dashed line in Fig. A.1. The 1980 design is shown at $f_N = 3.5$ and $E_E = 21$ kV/in.

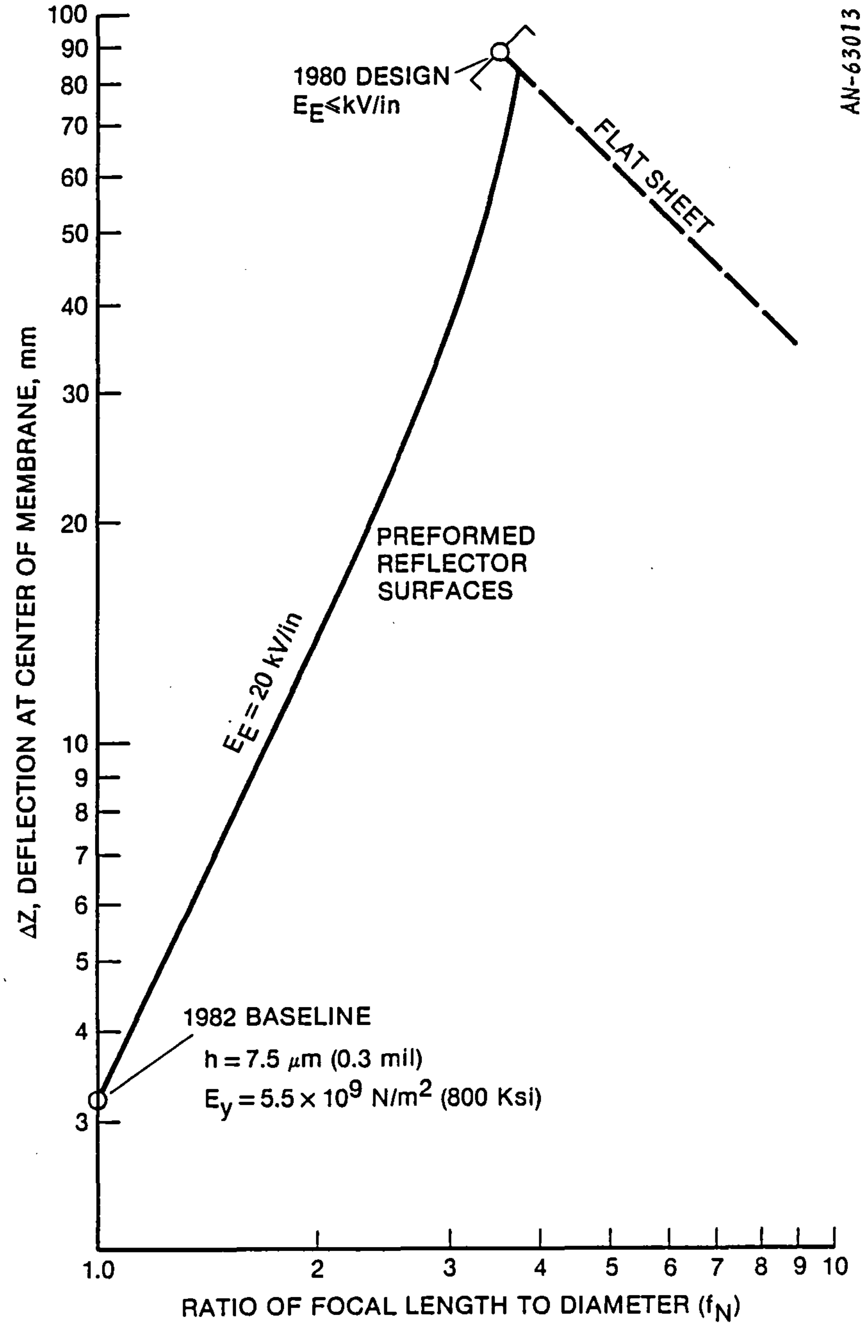


Figure A.1. Options When Using Different Preformed Membranes and a Fixed Field Strength E_E of 800 kV/m (20 kV/in).

Electric field strength varies along the dashed line. The 1980 design point is a practical upper limit for shaping a flat sheet. Notice that the central deflection decreases substantially from $f_N = 3.5$ to 1.0, the value selected as the 1982 baseline. The central deflection of this design is only 3 mm as compared to the 87 mm deflection of the 1980 design. The flat membrane required a substantial deflection before the necessary tension developed. The tension develops much more rapidly with preformed surface, and deflections are substantially less.

The minimum possible separation between the electrode surface and the membrane reflector is a function of the membrane's central deflection. A nominal electrode gap of twice the reflector deflection or 6 mm, combined with the 800 kV/m maximum field strength, yields a voltage of 4800 V, in contrast with the 40,000 to 60,000 V required in the 1980 flat-membrane design. This case, however, is a lower limit on what could be achieved by using a preformed electrode surface with the preformed membrane. Such a small gap between the membrane reflector and electrode surface necessitates an accurate layup of the electrode surface. But the EMR is a self-defeating approach if the electrode surface must be precise. Much of the value of the EMR concept resides in the orders-of-magnitude improvement in the reflector's surface quality as compared with the electrode surface. For this design to exhibit such a trait, the gap between the two surfaces must increase.

Figure A.2 gives an indication of the magnitude of irregularities inherent in the electrode surface design. It shows the departure of a flat electrode panel from an ideal sphere with the same curvature as the membrane reflector, at a representative location, $R/R_m = 0.75$. The departure from the sphere is shown as a function of focal ratio f_N for various angular widths of the flat gore panels. The departure Δ_{o-p} varies over the surface, but representative values are obtained at $R/R_m = 0.75$. More gores and larger f_N (flatter surface) make for smaller surface departures. The baseline electrode surface, $\theta = 30$ degrees and

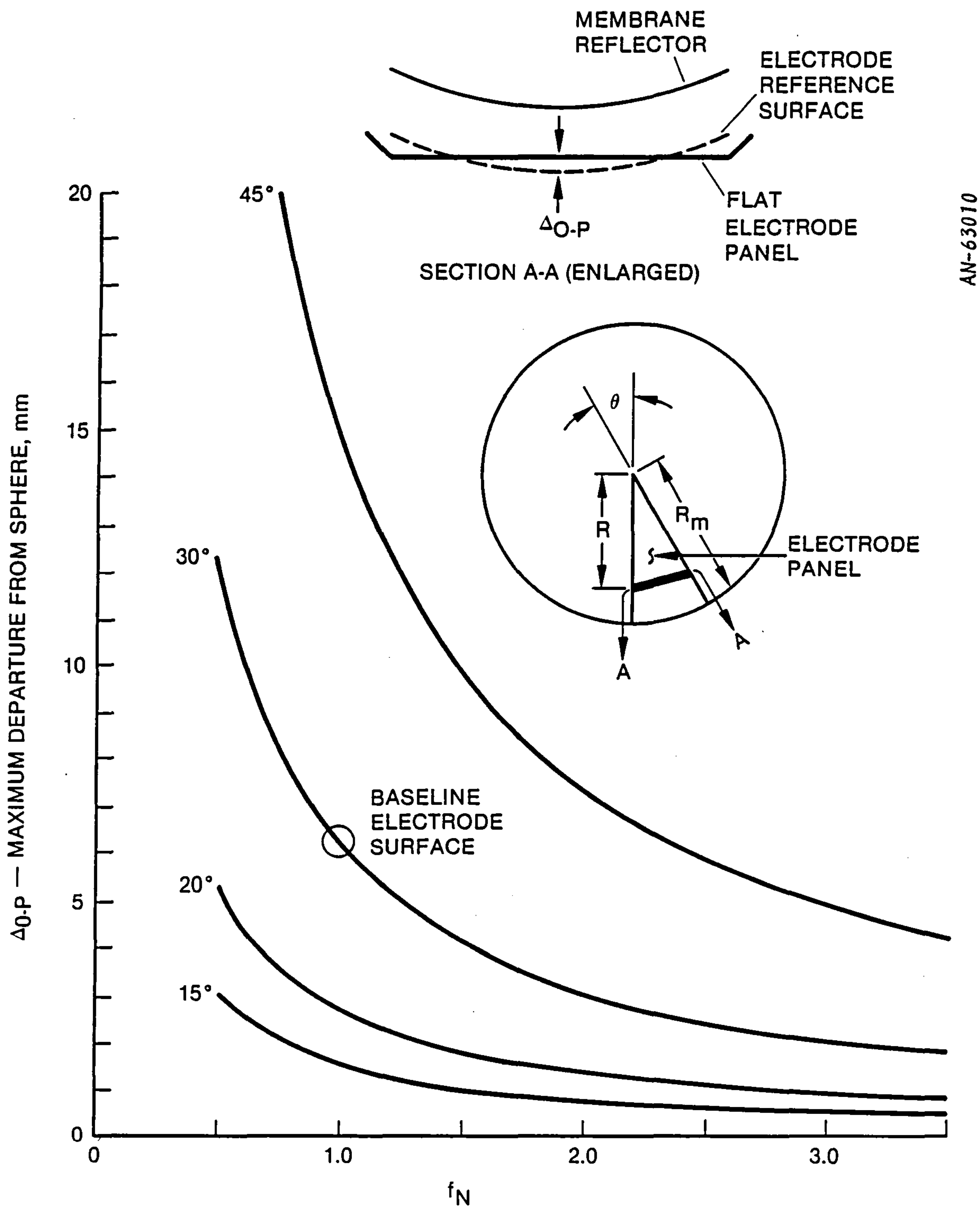


Figure A.2. Departure of Flat Electrode from Reference Surface at Radial Station R/R_m=0.75.

$f_N = 1$, exhibits a Δ_{o-p} of 6 mm. The mean electrode-to-reflector gap must be substantially larger than this departure. The design uses a mean gap of 50.8 mm or 8.5 times the electrode irregularity.

Table A.1 summarizes several possible electrode surface designs. The four options, which were considered in some detail, required 12, 24, and 96 drop cords. Option 4, using 12 drop cords and two rings of 12 panels, is the baseline. The 12 panels integrate well with the available 12-sided rim structure. A criterion for defining the ratio Δ/GAP will be discussed below. All four designs used a Δ/GAP criterion which results in a residual surface irregularity of 0.75 mm RMS. Options 1 and 4 have the highest voltages but provide the largest tolerance to electrode errors. Additional data will be provided subsequently on the voltages and field strengths of Option 4.

Figure A.3 shows that the electric field strength decreases from the center outward. This electric field strength is slightly less than those used in 1980 and 1981 with the flat membranes. The calculation of field strength depends in part on the stiffness and thickness of the membrane reflector. The data is presented for 7.5 μm (0.3 mil) Kapton, with a Young's modulus of 5.5×10^9 N/m^2 (800 ksi). Tests in 1980-81 indicated that 0.3 mil Kapton with 1000 A aluminizing on both sides has a Young's modulus of that value, which is substantially higher than the manufacturer's quoted value for uncoated Kapton. If future samples show a lower stiffness, the field strength requirement will decrease.

The electrode voltages for the three radial rings are shown in Fig. A.4. The radially varying voltage corresponding to the field strength in Fig. A.3 is labeled "ideal distribution with formed electrode". The three radial segments have voltages that approximate this distribution. Through a coincidence of spacing and loads requirements, the voltage variation is significantly smaller than that in the 1979 design, also shown in Fig. A.4. The five annular rings used in the 1979 design were conservative: three rings also worked well. With the small variation in the ideal voltage

TABLE A.1

POSSIBLE ELECTRODE ARRANGEMENTS

	Option 1	Option 2	Option 3	Option 4 (Baseline)
Focal ratio (f_N)	1.0	1.0	1.5	1.0
No. of Azimuthal Panels	12	24	12	12
No. of Radial Panels	3	5	3	3
No. of Drop Cords	24	96	24	12
Departure from Ideal, (Δ_{o-p}), mm	8.5	3.0	6.4	8.8
Δ_{o-p}/GAP*	0.17	0.275	0.17	0.17
Mean Electrode-to-Reflector Spacing (GAP), mm	50.8	11.4	38.6	50.8 (2.0 in)
Voltage at Center, kV	39	8.9	30.3	39
Voltage at Edge, kV	28	6.1	21.1	28

*For reflector surface accuracy of 0.75 mm RMS.

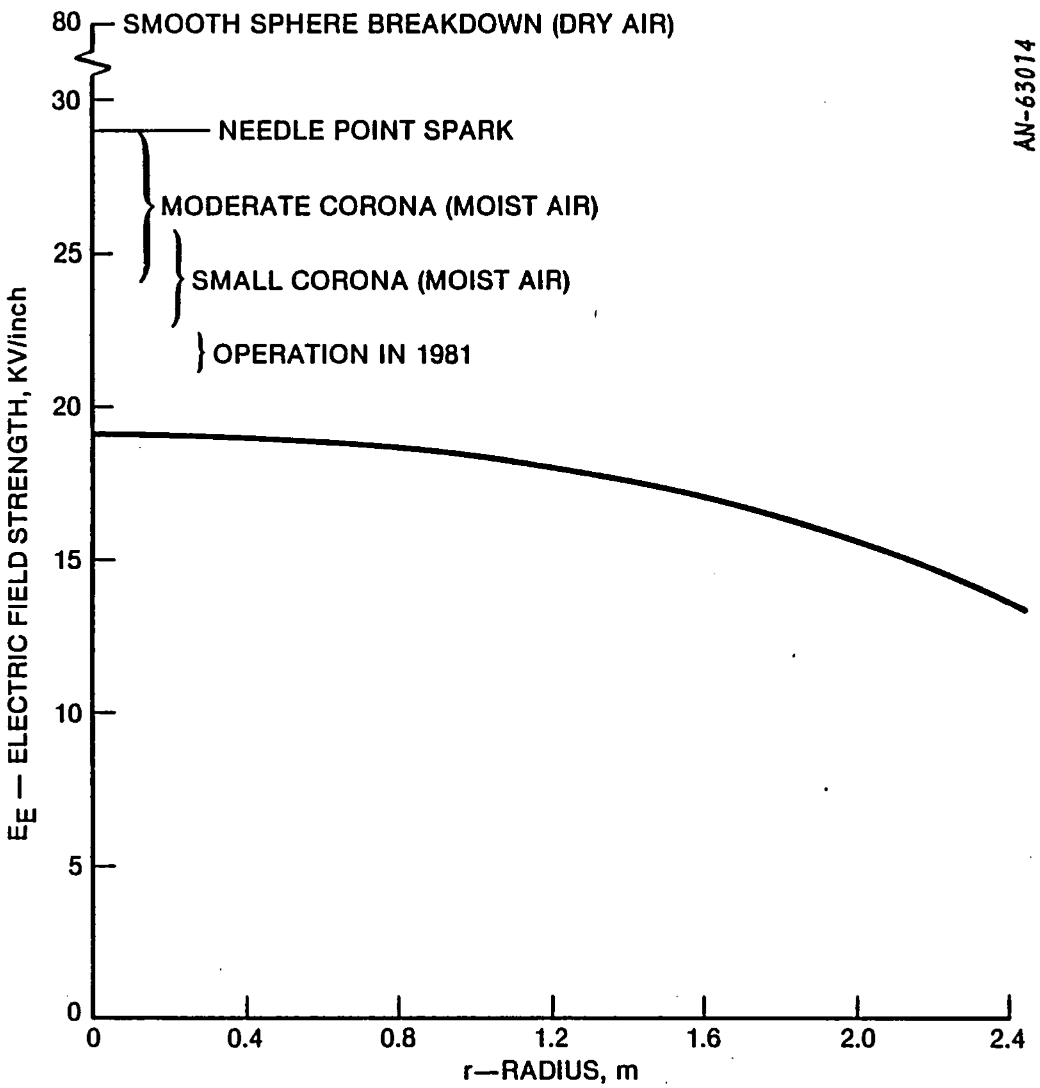
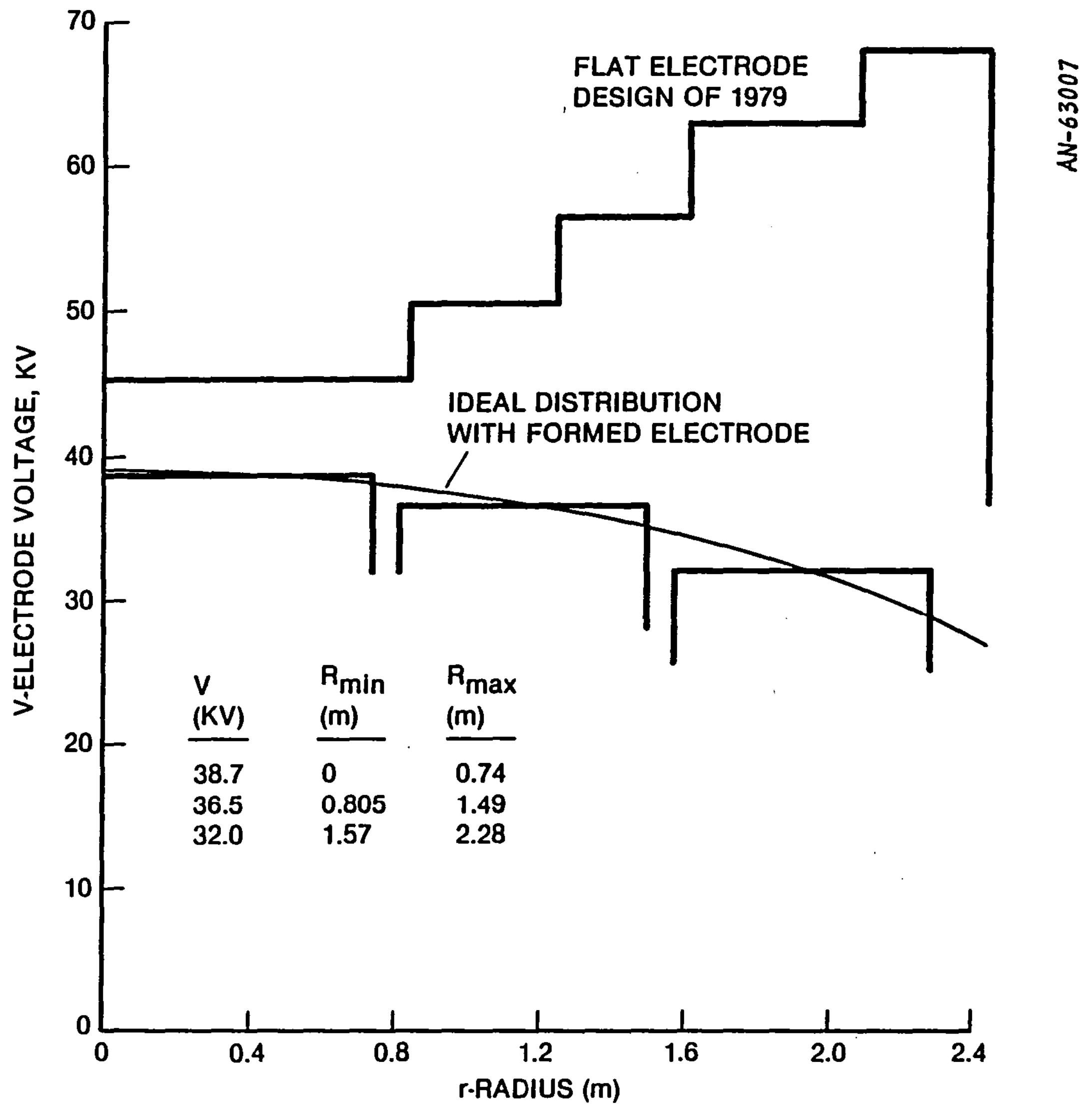


Figure A.3. Radial Variation of the Electric Field Strength



V (KV)	R_{min} (m)	R_{max} (m)
38.7	0	0.74
36.5	0.805	1.49
32.0	1.57	2.28

Figure A.4. Electrode Voltages

distribution for the new design, one or two rings would probably suffice if the flexible electrode assembly were accurate.

The effects of electrode irregularity are shown in Figs. A.5 and A.6 in a parametric form. Figure A.6 can be used to predict the effect of numerous electrode anomalies. It was developed using the results of individual computer runs of the type that produced Fig. A.5. The solid line in Fig. A.5 is the departure (error) in membrane shape from ideal caused by an assumed periodic error in the electrode. The electrode error in this case is Δ_{o-p} = 8.5 mm with a radial variation of sin $(R/2n\pi)$ where n = 2.5 cycles and R is the radius. This case is representative of the baseline discussed in this report. The RMS error for this case is about 0.75 mm. Also shown in Fig. A.5 is the gross deflection of the membrane from the unstressed to the formed condition. This configuration is significantly different than the 1979 design in that the errors in surface quality are a substantial fraction of the deformed shape. As mentioned previously, this result is somewhat unique to this small model. On 50 to 150 m apertures with f_N = 1, the membrane's central deflection will be 100 to 1000 times larger than the allowable membrane errors.

The effects of electrode waviness summarized in Fig. A.6 indicate that the EMR acts like a low-pass filter. High-frequency periodic pressure errors are substantially attenuated. The error is proportional to n^{-2} and directly proportional to the pressure error $\Delta P/P_o$ caused by the waviness. On a large EMR, the number of radial cycles would be 6 to 15 rather than 2.5 as in the 1982 baseline. Thus, this configuration is not a scaled representation of large antennas. The larger configurations would be less demanding on electrode waviness requirements to achieve the same RMS quality.

The last two figures in this appendix have to do specifically with the baseline design. Fig. A.7 summarizes the loads on the fibers during nominal operation. The electrostatic attraction force is indicated by the small arrows between the membrane reflector and the electrode membrane.

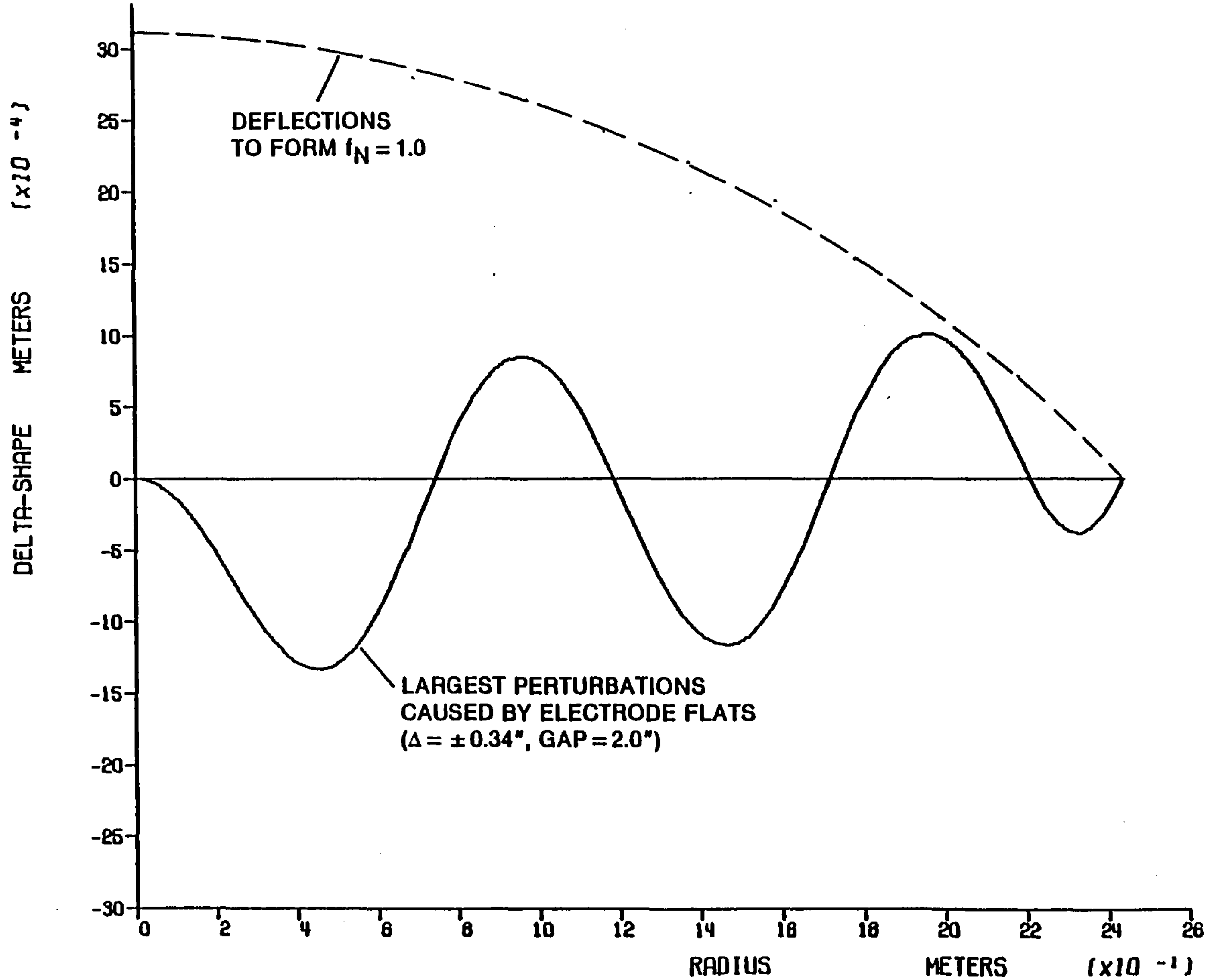


Figure A.5. Deflection of Reflector Surface Due to 8.5 mm Peak Error in Electrode Position

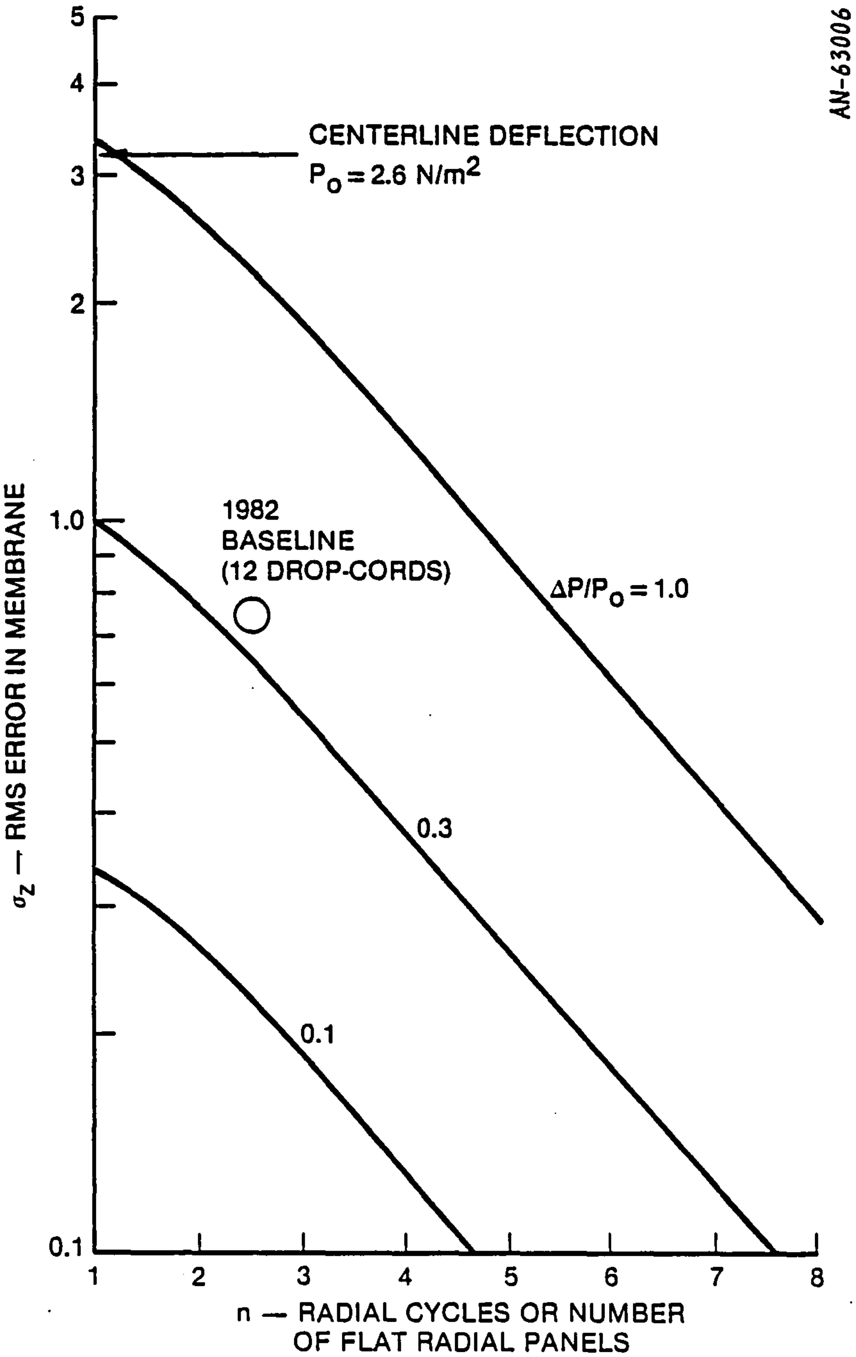


Figure A.6. Effect of Electrode Waviness on Membrane Reflector Quality

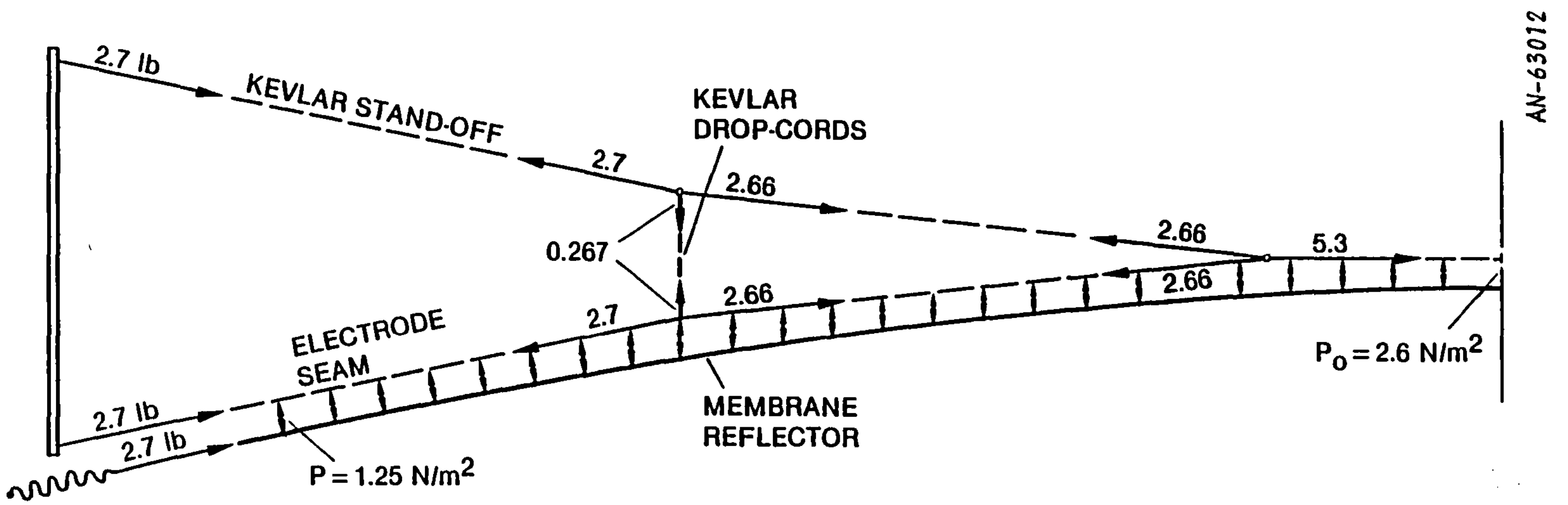


Figure A.7. Load Vector Increments Caused by Electrostatic Pressure, P_o

The attraction force ideally varies from 2.6 N/m^2 (3.7×10^{-4} lb/in^2) at the centerline to 1.25 N/m^2 (1.8×10^{-4} lb/in^2) at the catenary. A radial load of about 2.7 lb is exerted at the apex of each catenary and at the perimeter of the standoff cord. The load on each of the 12 Kevlar drop cords is only 0.267 lb. Using these loads, the required stiffness of the Kevlar standoff cords was determined. The Kevlar standoff cords alone prevent the electrode surface from excessive deflection toward the membrane reflector. The standoff cords were designed to limit the gross electrode surface deflection to one tenth of the membrane reflector's deflection, or 0.32 mm (0.012 in). Figure A.7 shows a spring attached to the apex of the reflector catenary. In early tests with the EMR, these "compensator" springs are not recommended.

Figure A.8 presents the results of a first-order calculation of the stiffness of the compensator springs. The criterion for the "range of interest" was the magnitude of vertical deflection at the catenary. A spring constant K of 80 lb/in would result in a deflection of the same magnitude as the central deflection without a spring. Thus, the membrane center would deflect about 6 mm and the catenary would deflect inward about 3 mm. A detailed design analysis is required to determine the radial and azimuthal stresses in the membrane. The analysis would lead to a detailed layout of the compensator's location, length, and kinematics associated with perimeter adjustments.

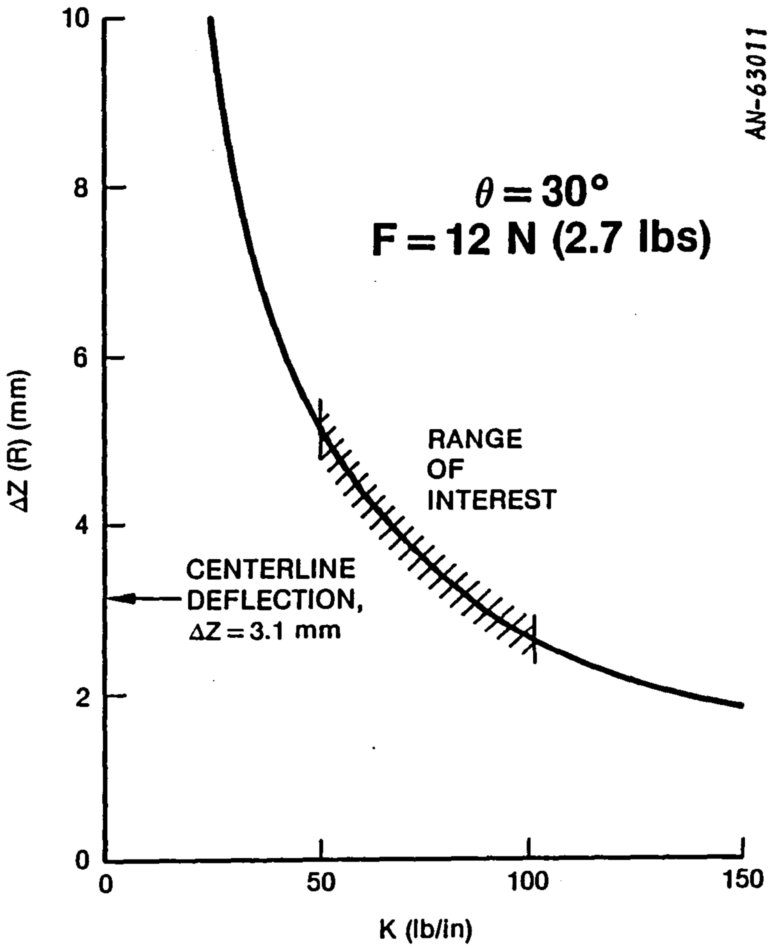


Figure A.8. Possible Perimeter Spring Compensator

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16. Abstract

Conceptual design studies have been completed on a new Electrostatic Membrane Reflector, EMR. The design is an improvement of a materials model tested in 1981. This new model incorporates both a preformed, curved membrane reflector and membrane control surface. This improved model is the second step toward a high precision large space antenna that could evantually exhibit a performance in terms of aperture diameter to surface quality exceeding 10^6. Design trades indicate that the goal of a low f_n-number (i.e., ratio of focal length to aperture diameter) can be achieved while operating in a humid sea-level environment. A nominal surface quality of 1.0 mm (RMS) is possible using available off-the-shelf commercial membranes. The design incorporates the rim structure and high voltage power supplies used on the 1981 materials test bed. Both the membrane reflector and control electrode surface are fabricated from 12 gore segments and attached to the available 12 sided, 4.88 m diameter rim. The preferred conceptual design has a f_n=1.0. The 4.88 m aperture is preformed with a centerline displacement of 0.306 m. The nominal spacing between the membrane reflector and the electrode control surface is 50.8 mm. The centerline membrane displacement from its preformed to its tensioned, smooth shape is about 3 mm. The membrane tensioning is achieved by application of an electrostatic pressure of 2.6 N/m^2 and a voltage of about 38 kV. This design incorporates an important trait of the full-scale designs: the only rigid structure of the antenna is the perimeter compression rim. Conceptually, the EMR is a highly packageable antenna. The electrode control surface is developed using two stiffened tension surfaces to form a type of "suspension bridge". EMR traits provide for a substantial improvement in surface quality of the membrane reflector over the electrode control surface. This will be important for large space structures desiring a ratio of aperture diameter to surface quality of 10^5 to 10^6 since the support structure precision need only be 10^3 to 10^4.

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