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# DOE PARABOLIC DISH SOLAR THERMAL ANNUAL PROGRAM REVIEW

# DEVELOPMENT AND TESTING OF THE SHENANDOAH COLLECTOR*

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## ABSTRACT

The test and development of the GE-designed 7-meter Shenandoah parabolic dish collector incorporating an FEK-244 film reflective surface and cavity receiver is described. Four prototypes tested in the Midtemperature Solar System Test Facility indicate, with changes incorporated from these development tests, that the improvements should lead to predicted performance levels in the production collectors.

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A parabolic dish solar collector was selected for the Shenandoah Solar Total Energy Project application because it could supply the design loads throughout the peak electrical demand period of the utility and do this from a limited (5-acre) field and under moderate (Atlanta area) insolation conditions. The collector was designed by the General Electric Company under a DOE contract for the design of the Shenandoah Solar Total Energy System.

The initial model upon which the final collector design is based evolved from a 5-meter diameter communications dish antenna which Scientific Atlanta had developed. A solar collector, which was called the engineering prototype collector, EPC, was fabricated by the expedient of applying a reflective film to the "petals" of the communication antenna and attaching a solar receiver where the cassegrain reflector was normally located. This EPC model was evaluated at the Sandia Solar Collector Module Test Facility, and it indicated the feasibility of adapting the low cost fabricating techrique of die-stamping petal sections to produce solar reflectors. These tests also led to modifications to the original receiver design resulting in improved receiver operation.

The reflector surface was originally conceived to be a glass surface over polished aluminum. The aluminum was a magnesium alloy which would polish to a high reflectivity. Alternatives were investigated, and an RTV silicone substitute for glass was developed when proprietary issues could not be resolved with the use of the GE glass process. An anodization scheme was carried on as an alternative. Both reflector approaches were eventually replaced by a reflective film (FEK-244, a 3M product). This change provided an improvement in reflectivity, enhancing the collection of solar energy to provide the thermal energy needs of the project. The change also indicated a protracted wash cycle could be considered over the other reflector approaches, making reduced operation and maintenance (O&M) costs possible. Since the aluminum was no longer the reflecting surface, the aluminum was changed to a lower cost alloy.

A key element in adapting the reflector film for dish collector use was the process development for applying FEK-244 to a compound curved surface. On the earlier EPC, the film was applied to the individual "petal" sections using the squeege/detergent hand application method which is recommended by 3M for laminating the film to flat panels. This was the first time the film had been applied to a compound curved surface so no historical precedent could be cited which would provide confidence as to the long term integrity of the film (remaining attached to the substrate) under all environmental conditions. The film was only a temporary expedient to convert a communications antenna to a solar collector. Thus, alternate approaches for a reflector were encouraged.

When it became evident, however, that the FEK-244 film offered significant advantages over the RTV or anodized alternatives, the problem of applying the film to a compound surface was readdressed. The solution turned out to be relatively simple. The FEK film was laminated to the flat aluminum substrate material prior to die-stamping into the "petal" shape. To protect the reflective film, an opaque premask film was laminated over the FEK. An additional benefit accruing from the easily peeled premask is that is also permits collector assembly outdoors without creating a concern over eye hazards. Both film and premask are applied using a roller applicator which reduces the time and labor over that associated with the hand application method. Environmental tests of two petals processed by the roller method disclosed the tendency of the FEK film to "tunnel." "Tunnelling" is a consequence of FEK expansion when exposed to hot, high humidity conditions and is the term applied to localized ridge-like lifting which occurs, especially at stress sites. FEK has a coefficient of thermal expansion of about 45 microinch/inch/°F. Resolution of this problem was effected by cutting the FEK every two feet to reduce the size of the laminated film sections. Subsequent environmental tests on petals with enlarged film sections (3-foot cuts) indicate no tendency toward tunnelling. This will reduce the number of cuts required in each "petal." Whether this phenomenon is associated primarily with the double curvature of a parabolic dish surface or is common even in a planar configuration, if the film sections are large enough, or whether roller application causes differences from hand applications is not known.

Four 7-meter diameter pre-production prototype dish collectors were fabricated for testing and evaluation in a quadrant of the Sandia Midtemperature Solar System Test Facility (MSSTF). Initially, the collectors had RTV-coated reflectors. One of the four was subsequently replaced with an anodized surfice and another with an FEK surface. All of the reflectors were assemblies of 21, 8-foot long "petals" and a 29-inch wide center annulus section. The two-part reflector was a consequence of the petal fabricator being limited to a press size which would only accommodate an 8-foot die. With the acquisition of a 900-ton press the fabricator can now stamp full-length petals, eliminating the need for the annulus section. The annulus was fabricated by a spinning operation. An improvement in the collector efficiency is expected with the extended petal design. On the quadrant test collectors, the annulus accounts for about 10 percent of the reflector area but contributes much less than the expected reflected energy due to the non-specularity of the spinning.

The collector to be installed at Shenandoah will incorporate several design changes as a result of the quadrant tests.

Difficulties evidenced in the assembly of the reflector to the declination axis prompted the change from trying to align two horizontal holes for attachment to the frame, to mating the flat surfaces to effect assembly.

The large amount of field welding of the frame assembly led to the use of a base support frame to permit the frame assembly to be shop welded and be field installed as a finished section. This procedure also permits the polar drive motors and jackscrews to be shop welded to the collector frame assembly and the entire assembly checked for proper polar rotation prior to shipment.

The difficulties encountered in maintaining the reference orientation for the position indicating potentiometers has led to a redesign of the mounting bracket and a change in the attachment to the rotating axes.

The mechanical stop on the jackscrews will be strengthened to prevent the gear motors from driving through the stops and causing the reflector to freely pivot about the polar axis.

Each time the receiver was brought into or taken out of focus, the aperture plate (made of stainless steel) received a healthy thermal input causing the aperture plate to buckle. The heating also lead to the malfunctioning of the optical fibre solar tracking system. A thicker steel sheet was not totally satisfactory. A quartz refractory pad is now used to insultate the aperture plate.

The receiver coil through which the heat transfer fluid is circulated has been changed from a double coil to a single coil. At flow rates slightly less than 1 gal/min through the double coil receiver, it was noted that a transition to laminar flow appeared to be occurring. The tubing diameter for the single coil has been enlarged to maintain the pressure drop at about 15 psi while maintaining the tube wall to fluid $\Delta T$ at less than 100°F at the minimum flow rates to keep the Reynolds number above 8200. The new coil was tested in a quadrant test collector and indicated improved operation in effecting heat transfer at low flow rates.

The hub, which is the centrally located element to which the reflector petals are attached, had been changed from an aluminum weldment to a steel weldment as a cost saving measure. Solicitations from potential fabricators now indicate that the hub can be made from an aluminum casting at an even greater cost savings, so this avenue is being explored further.

The collector was designed to meet the requirements indicated in Table 1. An operational characteristic which is distinctive to this dish collector is that the full temperature differential (from 500°F input to 750°F output) is accommodated in contrast to troughs where a number of collectors make up a $\Delta T$ string. The minimum operation level of 50 Btu/hr-$ft^2$ is the level at which the system losses (parasitic and thermal) are just met. The other requirements listed are common to other concentrating distributed collector systems. The design requirements were translated into collector optical and receiver thermal parameters and incorporated into a collector system analysis model. This model was used to analyze the collector performance in terms of key variables. These variables are shown in Figure 1.

The f/d ratio was selected on the basis of optimizing the concentration ratio without an undue increase in the receiver heat losses. Figure 2 shows the efficiency was maximized at a f/d ratio of 0.5

The sensitivity of the concentration ratio (CR) from 250 is shown in Figure 3. The collector for Shenandoah will have a CR of 234 with an 18-inch diameter receiver aperture.

The indicated reflectivity, Figure 4, is the level which, in conjunction with the intercept factor and receiver efficiency, was thought to be required to provide the overall collector efficiency needed to meet the collector design requirements. The FEK-244 surface on the environmentally tested panels has manifested a reflectance of about 0.85 after washing after degrading to about 0.82. On the Quad Test units, exposure to the elements for 3 months resulted in a reduction in the specular reflectivity (35 mr), but the level was recovered after washing.

TABLE 1. SHENANDOAH COLLECTOR DESIGN REQUIREMENTS

| | | |
|---|---|---|
| Type: | Concentrating, Two-Axis Tracking, Parabolic Dish | |
| Coolant Fluid: | Syltherm 800 | |
| Output: | 1.09 x $10^8$ Btu/Yr | |
| Operating Conditions: | • Ambient Temperature Range | : 17°F - 95°F |
| | Fluid ΔT | : 250°F |
| | • Max. Working Fluid Bulk Temperature | : 750°F |
| | • Wind Loads | : 30 mph |
| | • Tracking Range: Polar Axis | : 180-210° |
| | Declination Axis | : 15-90° |
| | • Insolation Levels | : Design - 200 Btu/$ft^2$-hr<br>Max. - 300 Btu/$ft^2$-hr<br>Min. - 50-75 Btu/$ft^2$-hr |
| Non-Operating Survival Conditions. | • Ambient Temperature Range | : -3°F to 104°F |
| | • Wind Loads | : 90 mph |
| | • Hail Impact | : 0.6 inch diameter |
| | • Lightning strike | : 100 kA peak current<br>1 Microsecond rise time |
| Maintenance, Routine: | • Reflective Surface Washable<br>• Receiver Cleanable without removal<br>• Control Calibration | } Design Provisions |
| Maintenance, Unscheduled: | • Disk petals replaceable<br>• Receiver replaceable<br>• Receiver/dish alignment<br>• Controls removable | } Design provisions |
| Hazard Shutdown: | • Defocus time | : 2°/sec minimum |
| | • Over temperature | : Automatic |
| | • Loss of fluid flow | : Automatic |
| | • Power loss | : Stand-by-power |
| | • Environmental | : Manual override |

| | |
|---|---|
| f/d | Focal Length to Dish Diameter Ratio |
| Concentration Ratio | Collector Aperture/Receiver Aperture |
| Reflectivity | Total Hemispherical and Specular Distribution |
| Slope Error | Deviation from a Paraboloid |
| Tracking Error | Receiver Offset from Solar Flux |

FIGURE 1. COLLECTOR DESIGN VARIABLES

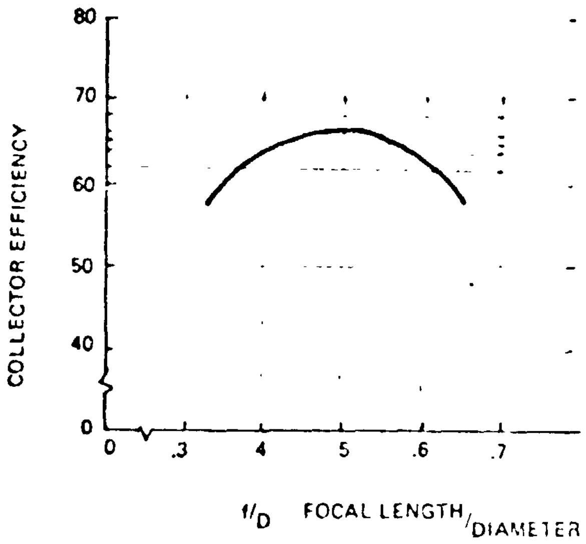

FIGURE 2. FOCAL LENGTH OPTIMIZATION

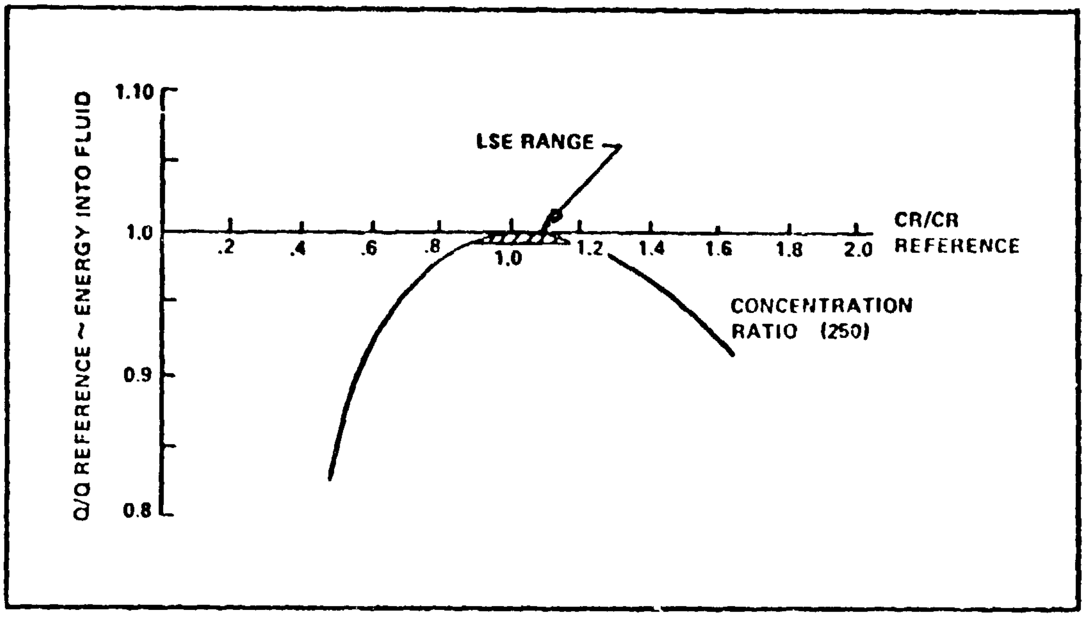

FIGURE 3. CONCENTRATION RATIO SENSITIVITY ANALYSIS

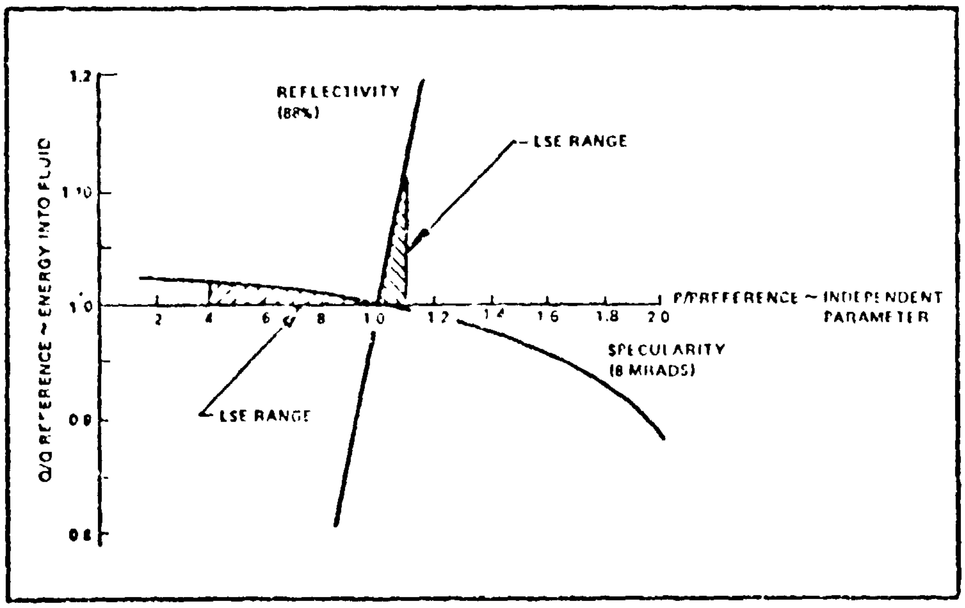

FIGURE 4. REFLECTOR SURFACE PARAMETER SENSITIVITY ANALYSIS

The intercept factor, which is defined as the percentage of the reflected energy incident at the receiver aperture, is a function of the specularity, slope errors, and tracking errors associated with the collector and is required to be about 0.96 to achieve the collector performance requirements. A slope error of 1/2 degree was considered a design parameter and its sensitivity relative to energy collection is shown in Figure 5.

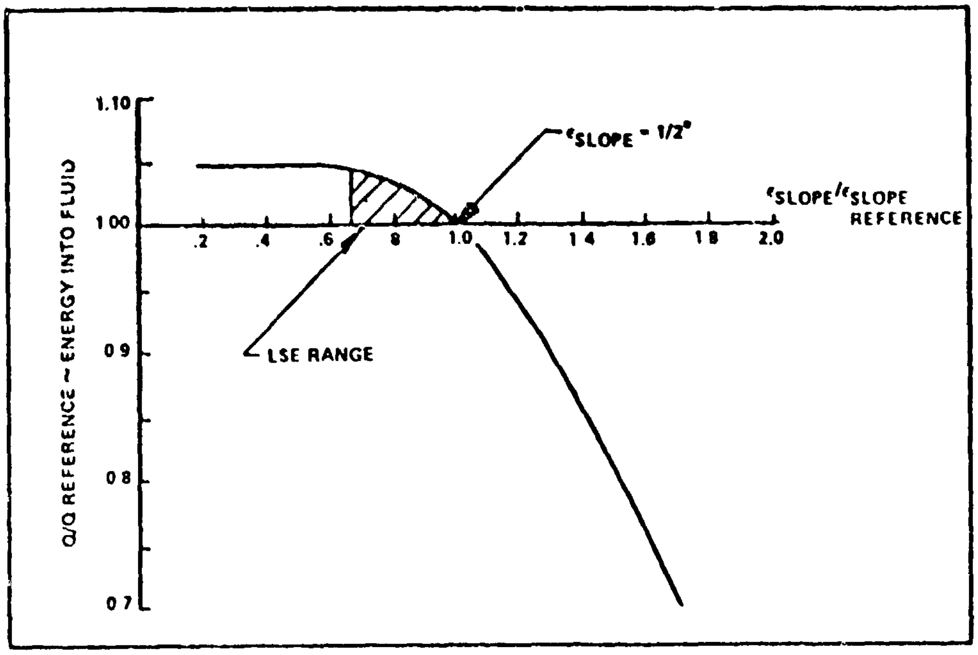

FIGURE 5. SLOPE ERROR SENSITIVITY ANALYSIS

The sensitivity of the tracking error on the energy collection is shown in Figure 6. The tracking bias of 1/4 degree was used as the collector design parameter.

The dish diameter of 7 meters was selected on the basis of being the best compromise considering collector cost, field cost, collector efficiency, and fluid heat losses. The diameter optimization results are shown in Figure 7. A collector field cost per unit of delivered energy versus collector diameter plot can be constructed for various projected collector costs. For our case, the optimal diameter lies in the 7-meter range. If collector costs can be reduced, other field component costs become more important, and the trend is toward optimizing at larger diameters.

These collector design parameters are shown in Figure 8, and the collector performance curves are indicated to show the expected off-design characteristics.

Quadrant test results from the FEK-244 collector indicate that these early prototypes are achieving operational levels very close to design levels. Production collectors, incorporating improvements suggested from the quadrant tests are expected to provide performance levels predicted.

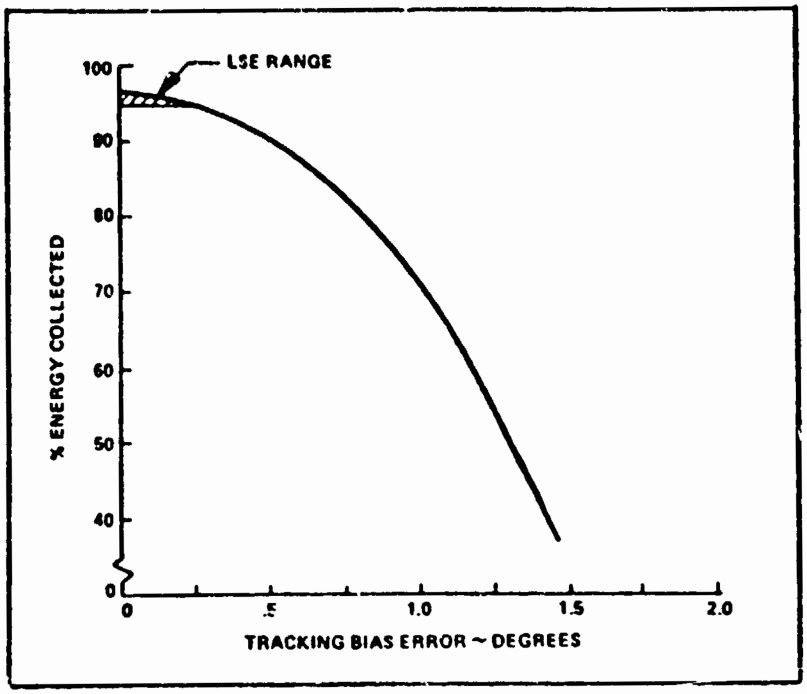

FIGURE 6. TRACKING BIAS ERROR SENSITIVITY ANALYSIS

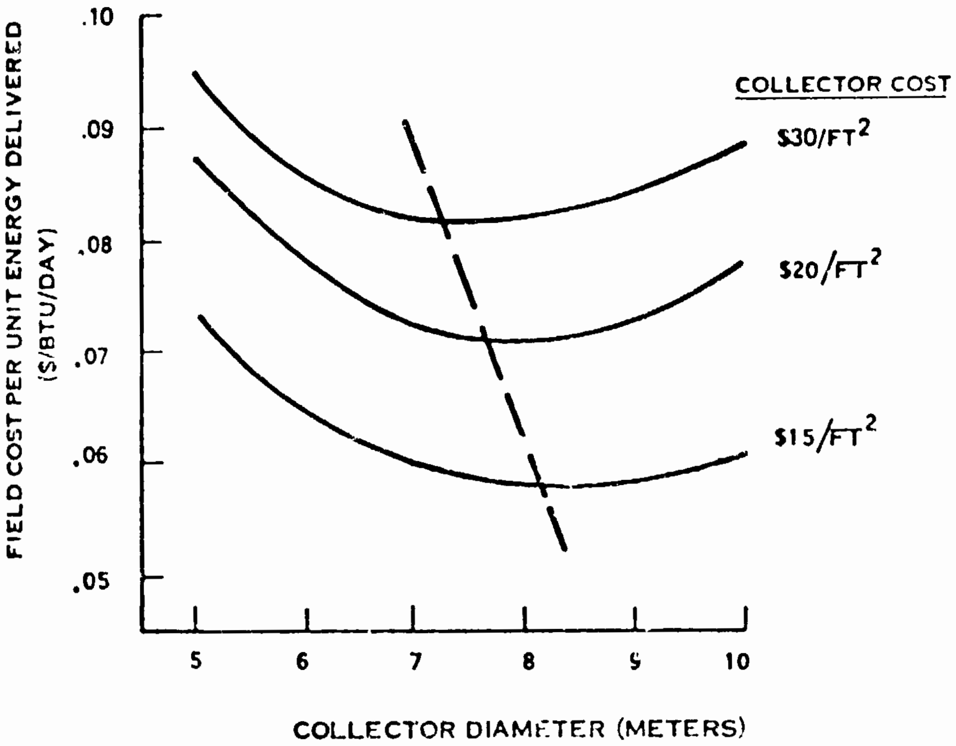

FIGURE 7. OPTIMIZATION RESULTS - COLLECTOR DIAMETER VS. COST/BTU DELIVERED

### COLLECTOR PARAMETERS

| PARAMETER | NOMINAL VALUE |
|---|---|
| $D_{DISH}$ | 7 METERS |
| CR | 25[illegible] |
| F/D | 0.6 |
| REFL | [illegible]8% |
| $\sigma_{SPEC}$ | 8 MRADS |
| $\sigma_{SLOPE}$ | 8.7 MRADS (1/2°) |
| $\sigma_{TRACK}$ | 4.4 MRADS (1/4°) |
| INSOLATION | 200 BTU/HR-FT$^2$ |
| $T_{IN}$ | 500°F |
| $T_{OUT}$ | 750°F |
| $T_{AMBIENT}$ | 50°F |

### NOMINAL DESIGN POINT PERFORMANCE

% CAPTURED BY RECEIVER = 96%

$Q_{RADIATION\ LOSS}$ = 7410 BTUH

$Q_{CONVECTION\ LOSS}$ = 3890 BTUH

$Q_{CONDUCTION\ LOSS}$ = 930 BTUH

$Q_{INTO\ FLUID}$ = 55,500 BTUH

COLLECTOR EFFICIENCY = 67%

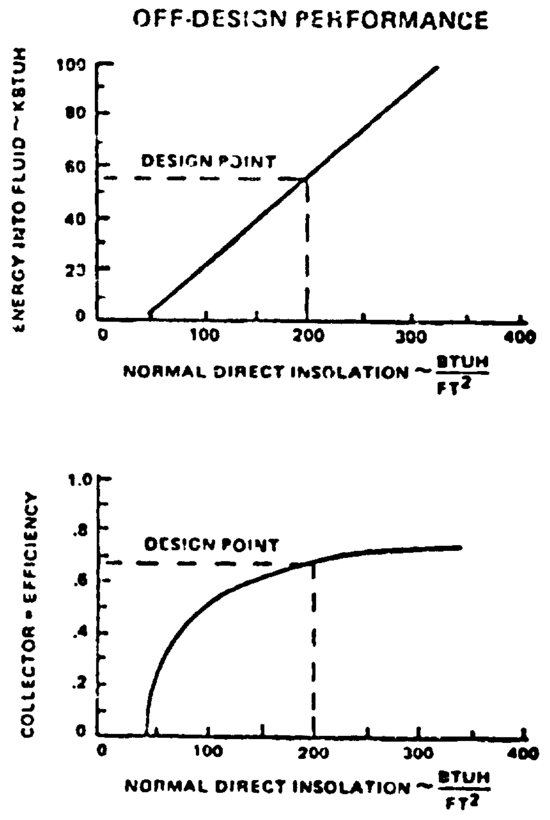

FIGURE 8. NOMINAL COLLECTOR PERFORMANCE AND DESIGN PARAMETERS