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Participation in Multilateral Effort to Develop High Performance Integrated CPC Evacuated Collectors

Final Report

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ABSTRACT

Throughout the past decade the University of Chicago Solar Energy Group has had a continuing program and commitment to develop an advanced evacuated solar collector integrating nonimaging concentration into its design. Our early pre-prototypes were fabricated in cooperation with GTE Laboratory in Waltham, Massachusetts. During the period from 1985-1987, some of our efforts were directed toward designing and prototyping a manufacturable version of an Integrated Compound Parabolic Concentrator (ICPC) evacuated collector tube as part of an international cooperative effort involving six organizations in four different countries. The participants included the University of Chicago and Colorado State University in the U.S., Sicover (a subsidiary of Corning, France), the DFVLR in Germany and The University of Geneva in Switzerland. This "multilateral"project made considerable progress along the path towards a commercially practical collector. One of two basic designs considered employed a heat pipe and an internal metal reflector CPC. We fabricated and tested two large diameter (125mm) borosilicate glass collector tubes to explore this concept. The other design also used a large diameter (125mm) glass tube but with a specially configured internal shaped mirror CPC coupled to a U-tube absorber. Performance projections in a variety of systems applications using the computer design tools developed by the International Energy Agency (IEA) task on evacuated collectors were used to optimize the optical and thermal design. The long-term goal of this work continues to be the development of a high efficiency, low cost solar collector to supply solar thermal energy at temperatures up to 250^{o}C. Some experience and perspectives based on our work are presented and reviewed. Despite substantial progress and very encouraging results from this initial cooperative effort, the stability of research support and the market for commercial solar thermal collectors were such that the project could not be continued. However it is clear that some cooperative path involving university, government and industrial collaboration and modeled after this original "multilateral" effort described in this report, remains the most attractive near term option for developing a commercial ICPC.

I. Introduction

In an effort to put together a cooperative plan to develop a manufacturable version of an Integrated CPC, extensive discussions were held at the Montreal meeting of the International Solar Energy Society in 1985. These meetings involved individuals representing six different organization from four different countries. The plan was to combine the concepts developed in prototype form in earlier in work at the University of Chicago with many of the design features of the already commercialized evacuated flat plate collector tube being manufactured by SICOVER, a subsidiary of Corning France. The U. S. participants were the University of Chicago, Colorado State University, and Corning Glass Works, while the European participants were SICOVER, the University of Geneva in Switzerland, and the DFVLR (now the DLR) in Germany. Based on these discussions, formal proposals were submitted to the various responsible governmental agencies for such an international "multilateral" effort and a project at the University of Chicago was funded by the U. S. Department of Energy at a level of $30,000. This one year project (later extended at no additional cost to eighteen months) was intended to be the first year of a planned two-and-a-half year to three year project. Due to limited governmental resources and changes in the financial condition of some of the participating organizations, the full project was never carried out. However a great deal of design effort and prototype development was carried out and much was learned. This document is the final report for the University of Chicago portion of that project.

II. Background and History

CPCs are one family of a whole class of optical devices based on nonimaging design principles (1,2) which maximize the geometric concentration ratio (collecting aperture to absorber area ratio) for a given angular field of view. The great advantage of CPC collectors for solar energy collection is that the field of view, characterized by the half-angle of acceptance, q_c , can be made large enough so that active tracking of the sun can be eliminated while still achieving enough concentration to be useful. A choice of q_c equal to $\pm 35^o$ permits collection of direct beam insolation for a minimum of 7 hours per day throughout the year with a completely fixed collector mount and can achieve a geometric concentration ratio of 1.7 X . It is this configuration that formed the baseline for the design evolution of the CPC (3). The first versions, developed at Argonne National Laboratory, used external reflectors coupled to evacuated dewar type absorbers and led to commercial collectors manufactured by the Energy Design and Sunmaster Corporations. Shortly later it became clear that considerable improvement in performance and potential manufacturability could be had by integrating the reflector and absorber into an evacuated tubular module (4). This led to the collaborative program between the University of Chicago and GTE Laboratories to integrate the CPC optics into the design. The optical and mechanical design features of this experimental tubular collector (referred to as the ISEC for Integrated Stationary Evacuated Concentrator), are shown in Figure 1. The essential features of this original prototype design are 1) the evacuated glass enclosure shaped to the proper nonimaging concentrating profile, 2) a thin silver reflecting surface, vacuum deposited directly on the inside of the shaped glass profile, and 3) a steel flow-through absorber tube coated with a spectrally selective (high absorptance, low emmitance) surface (6)

Several years ago, about one-hundred prototype tubes based on this concept were fabricated and a test panel successfully demonstrated superior high temperature performance during more than three years of testing at the University of Chicago (7). construction of this pre-prototype panel was a joint project of the University of Chicago and GTE Laboratories in Waltham, Massachusetts. It used a tube design in which the CPC was formed by shaping and silvering the inside of outer glass tube and demonstrated superior performance and long life in a series of tests over nearly five years at both the University and Argonne National Laboratory. This collector demonstrated the highest efficiency at high temperatures ever achieved by a stationary collector. For example the instantaneous operating efficiencies measured at 120°C and 175°C were approximately 55% and 50% respectively. In addition this collector was operated at the highest temperature ever reached with a stationary collector when an efficiency of 44% was measured at an average collector temperature of 270° C. The performance remained at these levels from the beginning of the testing period in 1981 until the panel was transferred to Argonne National Laboratory for further tests in 1984. Subsequently the Integrated Compound Parabolic

Concentrator (ICPC) remained a highly successful experimental concept which demonstrated that very efficient high temperature performance from fixed non-tracking concentrators was a technical reality.

Because of the high optical efficiency and very low thermal losses, the expected thermal efficiency for Integrated CPCs is excellent. For example, in Figure 2, the performance curve determined by a fit to the measured performance of the ISEC is compared with that an advanced ICPC and the Corning "evacuated flat plate" commercial collector (the CORTEC™ collector).

If the solar thermal source is ever to be effective for widespread use in the temperature range from 100°C to 300°C, for both small scale and diffuse climate applications, it will have to be done with CPCs. An advanced CPC collector will provide an efficient source of high temperature solar thermal energy with an inexpensive and uncomplicated system. This will be as competitive or more competitive with natural gas and fossil fuels for any application at these temperatures as flat plate collectors are at domestic hot water temperatures.

For these reason it was felt that every effort should be made to expedite the transfer of the technology to the commercial market and an international cooperative effort to carry this out seemed ideal. Our proposed design used a large diameter (125mm) borosilicate glass tube with a specially configured internal shaped mirror CPC coupled to a U-tube absorber. In the remainder of this report, we review the designs considered and describe the fabrication and preliminary test of two large prototype tubes completed under this project.

III. Alternative "Multilateral" Concentrator Designs

There are several important features of tube design (besides concentration ratio, absorber emmisivity and vacuum quality) which affect the thermal performance. These include potential losses through any internal absorber supports as well as conduction losses where the absorber penetrates the tube end. Furthermore, once the heated fluid leaves the thermally efficient vacuum envelope, parasitic thermal losses set in which degrade the overall collector efficiency (8,9). Therefore the absorber configuration and its effect on the fluid transfer path between individual tubes also contribute significantly to overall system performance. Finally, the sensible heat associated with the fluid inventory contained in a conventional absorber, which must be supplied from collected solar energy to reach elevated operating temperatures, can make a substantial contribution to the total parasitic heat losses and is directly related to the size, shape and hydraulic design of the absorber , as well as to the size, scale and shape of the outer glass tube. Thus these considerations interact with the overall collector design including the concentrator optics and led us to consider a variety of absorber and concentrator configurations. Alternatively, the use of heat pipes can significantly reduce parasitic thermal and mechanical losses by permitting innovative manifolding designs and eliminating pressure drops across individual collector tubes (8). These considerations had a strong impact on the specific designs reviewed for this project.

Over the eighteen months of the project our research efforts were directed towards designing and prototyping a manufacturable version of an ICPC , in particular a large tube version, 125mm (5 inches) in diameter, compatible with the commercial design manufactured by Corning France (the CORTEC collector). This became the conceptual basis for our international "multilateral" effort to develop an advanced evacuated CPC. We considered two different conceptual designs (11). Both concepts employed a shaped metal internal CPC mirror and had a single-ended heat extraction systems.

The Glass Absorber/Heat-Pipe version

We built and conducted preliminary tests on two prototype units of a large tube ICPC collector. These were similar to the CORTEC design but used a separate heat pipe for heat extraction. Alternative design profiles are shown in Figure 3. The absorber is a round glass tube with inserted metal heat pipe for heat extraction. Profiles for three different design acceptance angles corresponding to 35°, 40°, and 45° are shown. Side and top views of the large glass tube collector are illustrated in Figure 4, showing several mechanical features such as the absorber and mirror positioners and the heat pipe. For sentimental and somewhat historical reasons we referred to this configuration as the "Monaco II" collector.

The experimental effort provided a practical context for continuing work on remaining materials issues. In particular we tried to identify the best methods for yielding the highest possible reflectivity surface for the internal mirrors and to select among several options for the selective coating. Finally it provided some evidence of potential problem areas in such an all glass system. In particular, we found that the metal heat pipe was somewhat less effective in removing the heat from the absorber and the mechanical contact between the metal heat pipe and the glass absorber appeared to pose a possible threat to the integrity of the collector.

The metal U-tube hydronic flow-through absorber design

This design is illustrated in various stages of conceptual development in Figures 5-8. It too uses a large diameter (125mm) borosilicate glass tube but has a specially configured internal shaped mirror CPC coupled to a U-tube absorber. A CPC profile designed for an elongated oval virtual target will accommodate a real U-tube absorber as shown in Figure 5. One advantage of this configuration is that since the reflector touches the virtual absorber (although not the real one) the optical "gap -losses" are zero. Another interesting fact is that the net real concentration is slightly lower than the theoretical maximum since the real absorber is larger than the virtual surface, however this loss in concentration is slightly compensated for by a higher optical efficiency resulting from a cavity absorption enhancement effect.

Profiles for three different design acceptance angles corresponding to 35^{o}, 40^{o}, and 45^{o} are shown in Figure 6. Figure 7 shows the Detailed cross-section profile for the large scale ICPC design selected as the basis for this project and designated the "multilateral design". It uses an internal shaped metal reflector coupled to a U-tube absorber made of 14 mm O. D. copper tubing

Finally , side and top views of the collector showing the absorber and mirror positioners are illustrated in Figure 8. The single ended U-tube absorber does not require a bellows and uses glass-to-metal seals identical to those in the CORTEC collector. Performance projections in a variety of systems applications using the computer design tools developed by the International Energy Agency (IEA) task on evacuated collectors were used to help optimize the optical and thermal design.

IV. Summary and Conclusions.

Despite substantial progress and very encouraging results from the initial cooperative effort, the stability of research support and the market for commercial solar thermal collectors were such that the project could not be continued. During the course of the effort, the Corning France subsidiary, SICOVER was sold the productions rights and facilities for manufacturing the CORTEC collector to SOLECO, an independent French company. Subsequently, substantial delays in implementing the original plans occurred. Our initial understanding was that SOLECO wanted to proceed with the project, which called for them to provide us with the $6000 necessary to fabricate the internal CPC reflectors, but no formal commitment was ever made, communications were poor and eventually broke down.

We next began a small collaborative effort with Fournelle of Canada. This company is the manufacturer of what used to be the "Philips collector", a technically very successful European evacuated tube collector which uses a 65mm outer tube of borosilicate glass and a simple flat fin absorber coupled to a copper heat pipe. We designed an internal CPC concentrator which was compatible with their external tube, seal and heat pipe configurations and agreed to fabricate reflectors for a small number of pre-prototype ICPC-ETC units. The plan was for Fournelle to incorporate these into assembled units compatible with their design and manufacturing constraints. This would have complemented other Fournelle efforts by providing a preliminary opportunity for them to gain valuable experience in forming the metal substrates for the mirrors and in developing practical methods for implementing several other features common to integrated concentrator designs. However when further support for the U. S. part of the effort was not able to be continued, the entire effort was suspended.

To this day the advanced Integrated CPC (ICPC)remains the only simple and effective method for delivering solar thermal energy efficiently in the temperature range from 100°C to about 300°C without tracking. It provides an efficient source of solar heat at these temperatures and makes practical and economical several cooling technologies which are otherwise not viable. When driven by these collectors, such advanced cooling technologies as double-effect or multi-stage regenerative absorption cycle chillers or high temperature desiccant systems will have significantly improved performance and can achieve an overall system co-efficient of performance high enough to be economical in a wide variety of applications. Even the best flat plate collectors cannot deliver the required high temperatures and thermal performance. Furthermore, tracking parabolic troughs are not likely to be practical in residential scale systems or effective in many environments where cooling is desired. The ICPC is the only high temperature nontracking option available.

Some cooperative path involving university, government and industrial collaboration and modeled after the original "multilateral" effort described in this report, remains the most attractive near term option for developing a commercial ICPC in collaboration with a manufacturer, hopefully by now a domestic U.S. manufacturer. In the past, the management of GTE incorporated has been very enthusiastic about the long term prospects for the ICPC and has indicated a willingness to collaborate closely with us in efforts to develop a detailed mechanical design which will incorporate practical solutions to the few remaining technical barriers. The ICPC design is by now conceptually well defined and should result in a superbly performing, conveniently deployable, high temperature collector tube, producible in high volume at low cost. A commercial partner could participate in the program by helping with final design studies, advising on the prototype design and fabrication, and carrying out manufacturability analysis and systems applications studies. In this way the program could have the benefit of their industrial expertise while they remain apprised of the most advanced technical developments. Such a company would be prepared to increase its level of activity when renewed environmental concerns and the realization that conventional fuels are being depleted inevitably generates a new market for solar thermal collectors.

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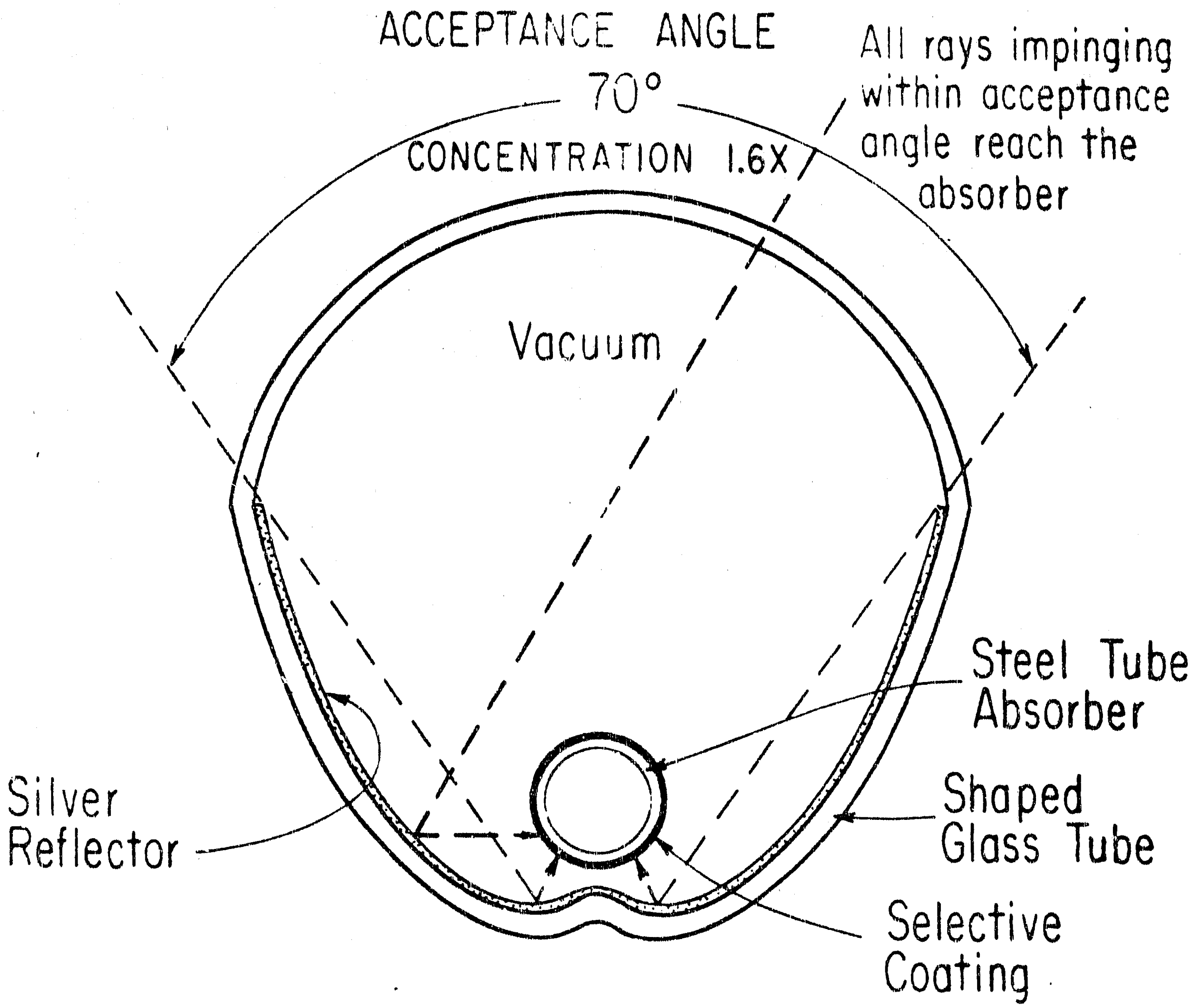
ACCEPTANCE ANGLE
70°
CONCENTRATION 1.6X
All rays impinging within acceptance angle reach the absorber
Vacuum
Steel Tube Absorber
Silver Reflector
Shaped Glass Tube
Selective Coating

FIGURE 1

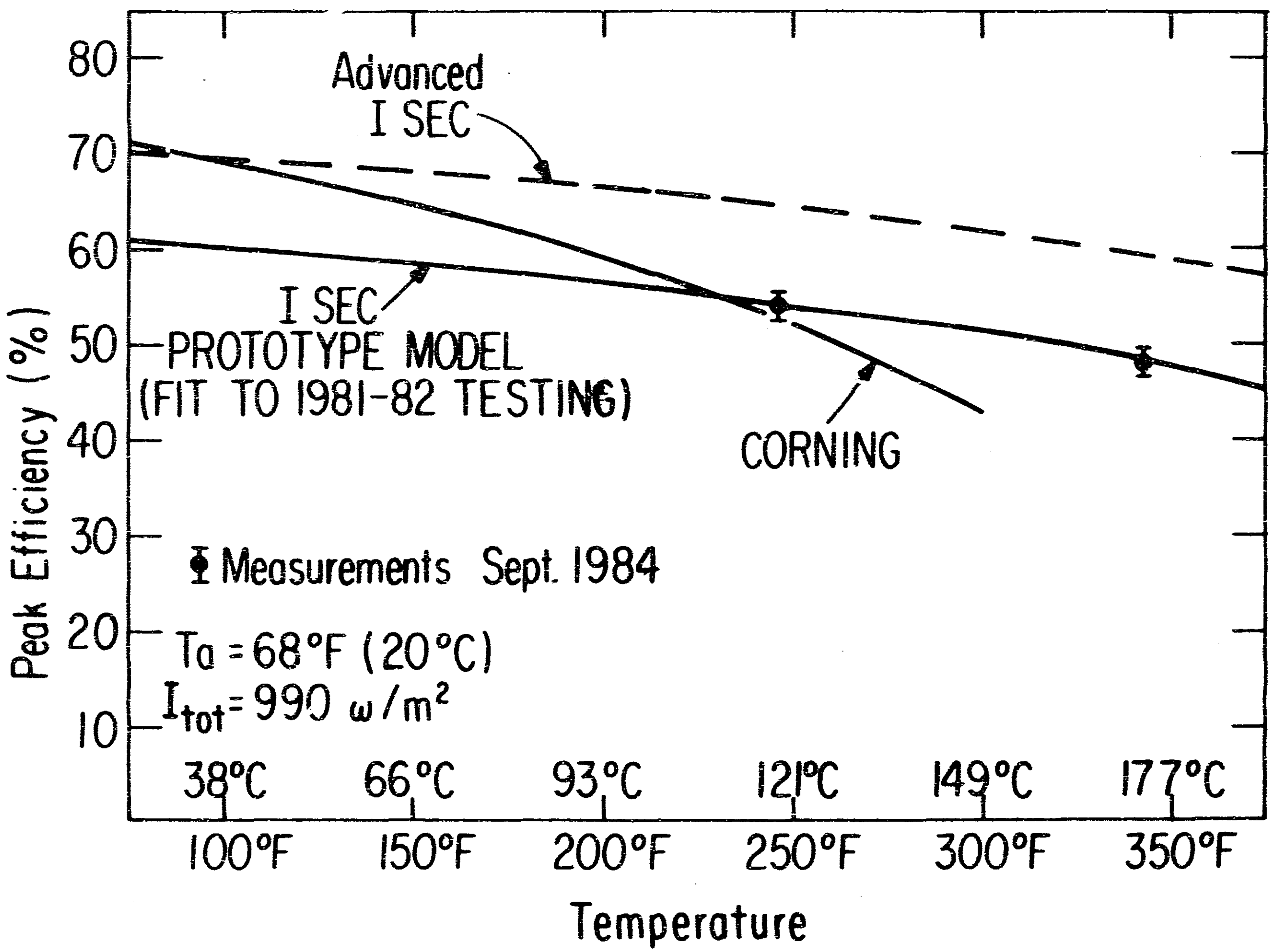
80
70
60
50
40
30
20
10
Peak Efficiency (%)
Advanced
I SEC
I SEC
PROTOTYPE MODEL
(FIT TO 1981-82 TESTING)
CORNING
Measurements Sept. 1984
Ta = 68°F (20°C)
Itot = 990 ω/m²
38°C
66°C
93°C
121°C
149°C
177°C
100°F
150°F
200°F
250°F
300°F
350°F
Temperature

FIGURE 2

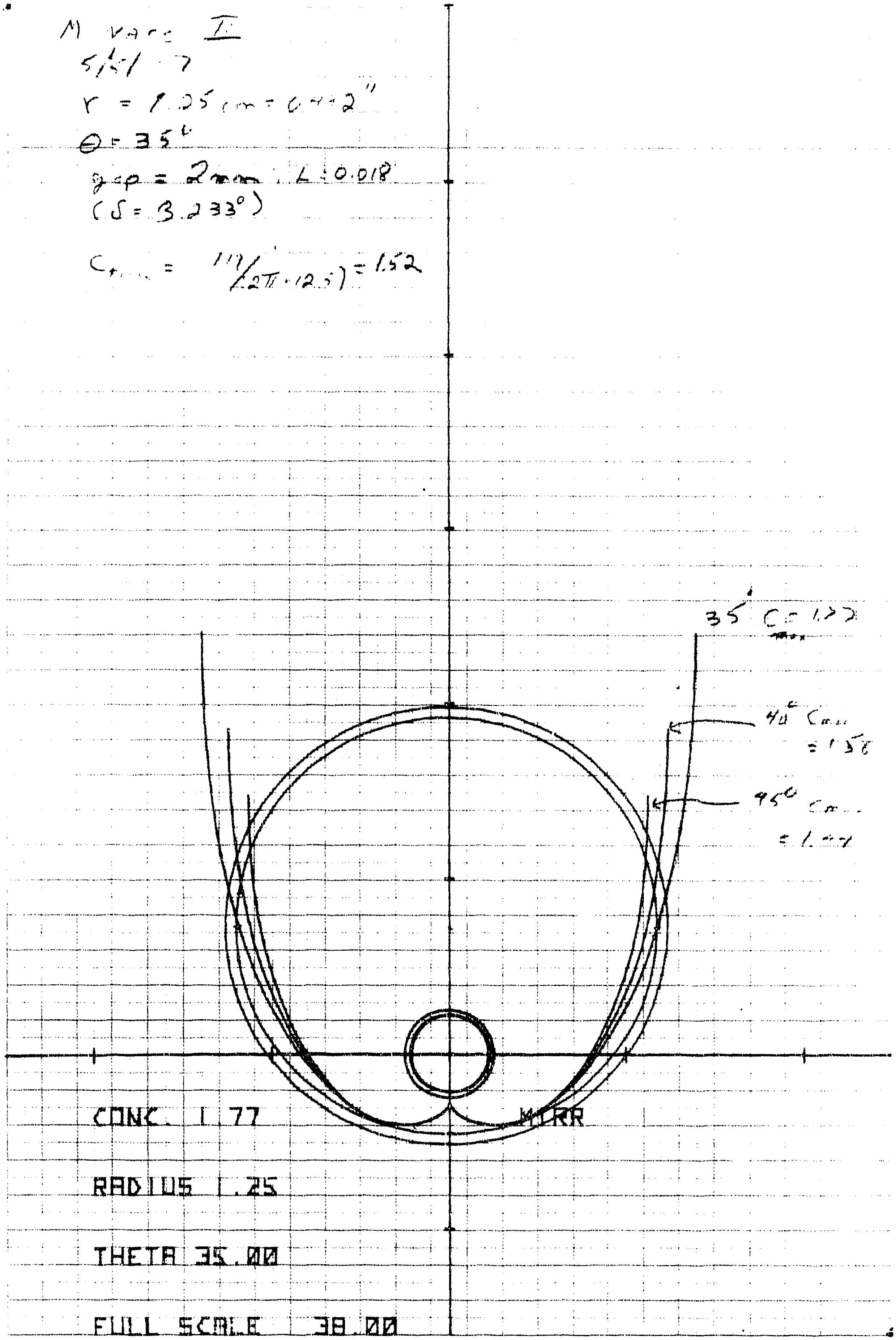
θ = 35°
(δ = 3.233°)
= 1.52
CONC. 1.77
MIRR
RADIUS 1.25
THETA 35.00
FULL SCALE 38.00

FIGURE 3

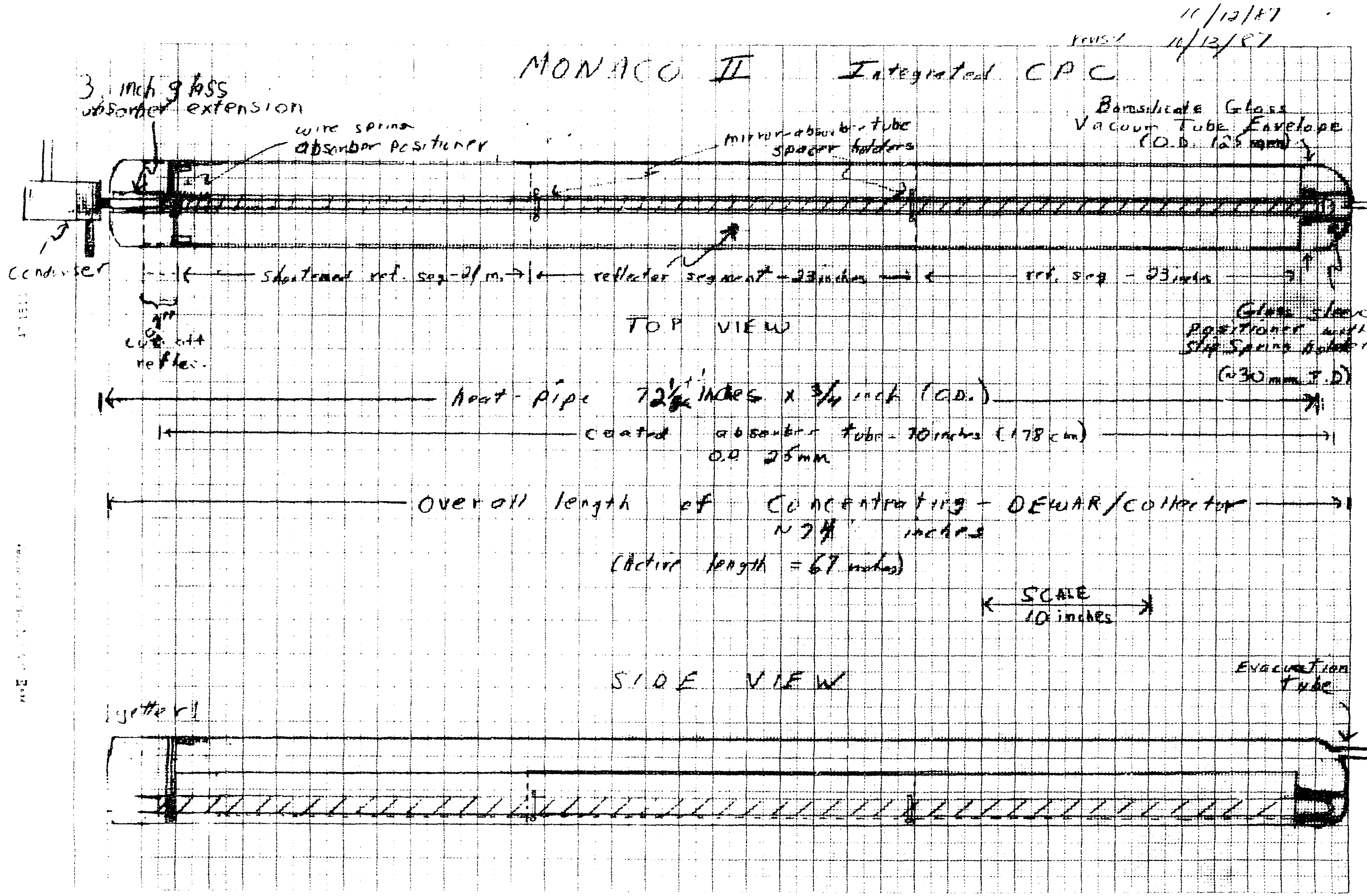
MONACO II Integrated CPC
3 inch glass absorber extension
wire spring absorber positioner
mirror-absorber tube spacer holders
Borosilicate Glass Vacuum Tube Envelope
condenser
reflector segment - 23 inches
ref. seg - 23 inches
TOP VIEW
Heat-pipe 72 1/4 inches x 3/4 inch (O.D.)
coated absorber tube - 70 inches (178 cm)
O.D 25 mm
overall length of Concentrating - DEWAR/collector
(Active length = 67 inches)
SCALE
10 inches
SIDE VIEW
Evacuation Tube
getter

FIGURE 4

Profile of CPC with Elliptical Absorber
Acceptance angle = 30.0 degree
Radius of Absorber = 7.0 mm
Gap between CPC and Absorber = 0.0 mm

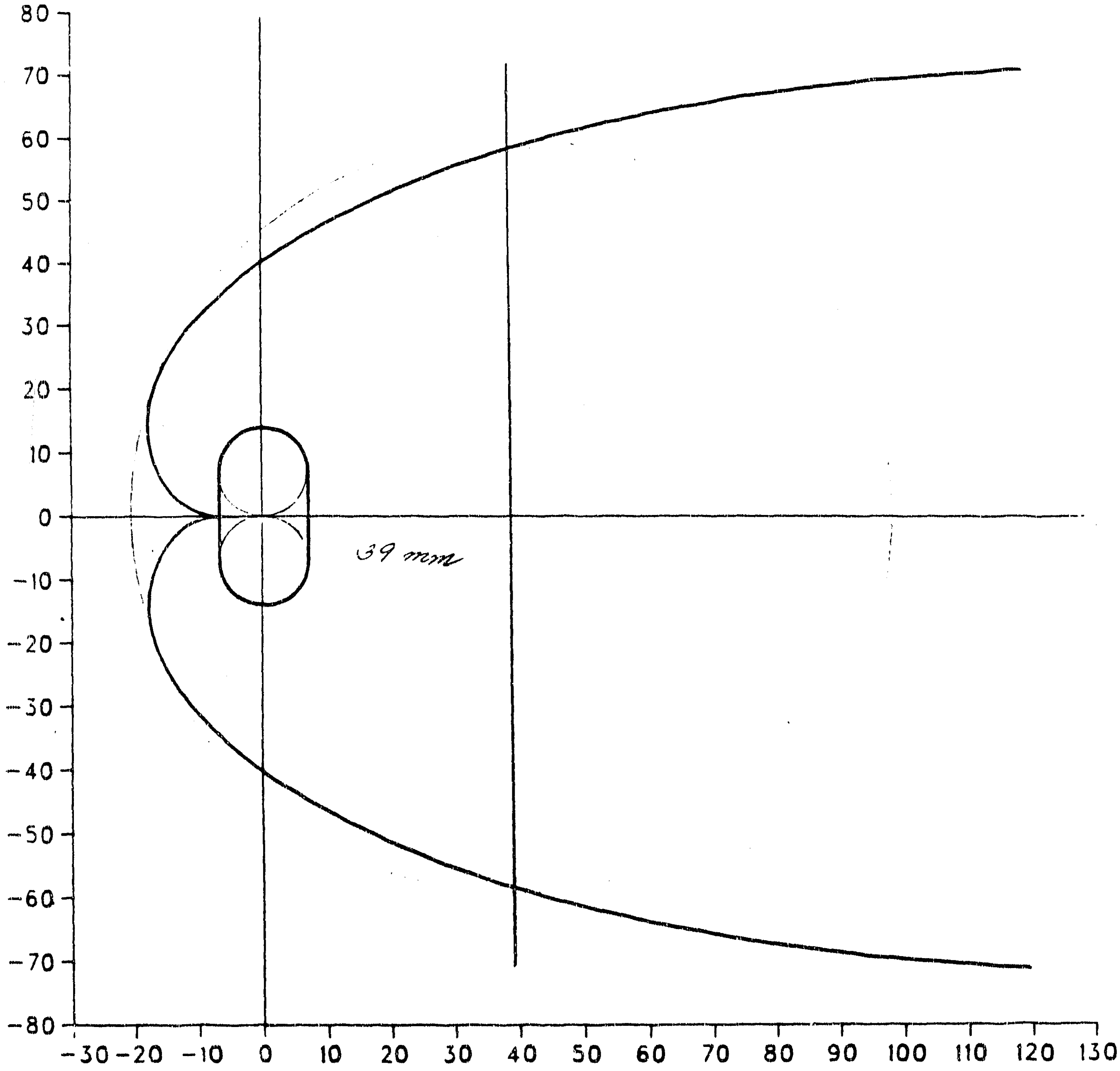

FIGURE 5

VIR. CONC. 1.74

RADIUS 0.70

THETA 35.00

GEOM. CONC. 1.43

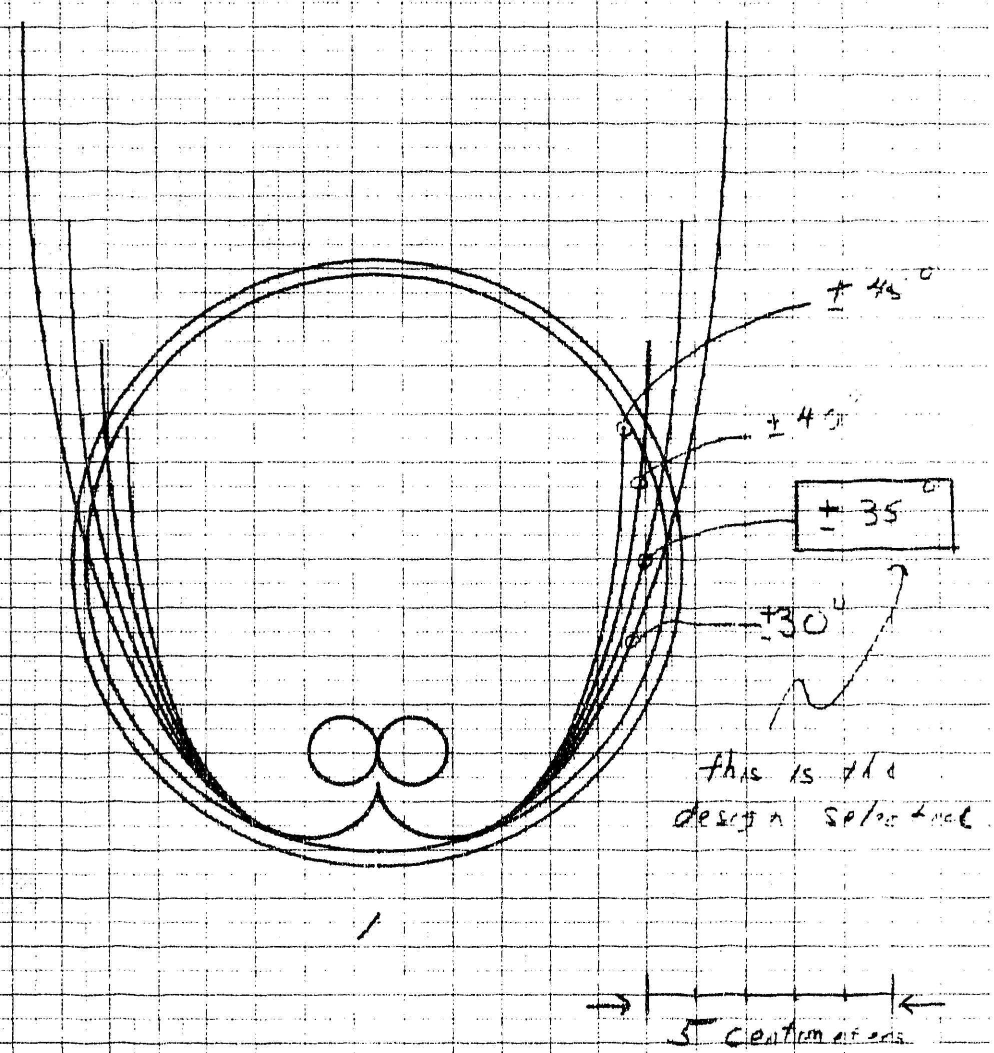

FIGURE 6

PROFILE OF LARGE SCALE INTEGRATED CPC

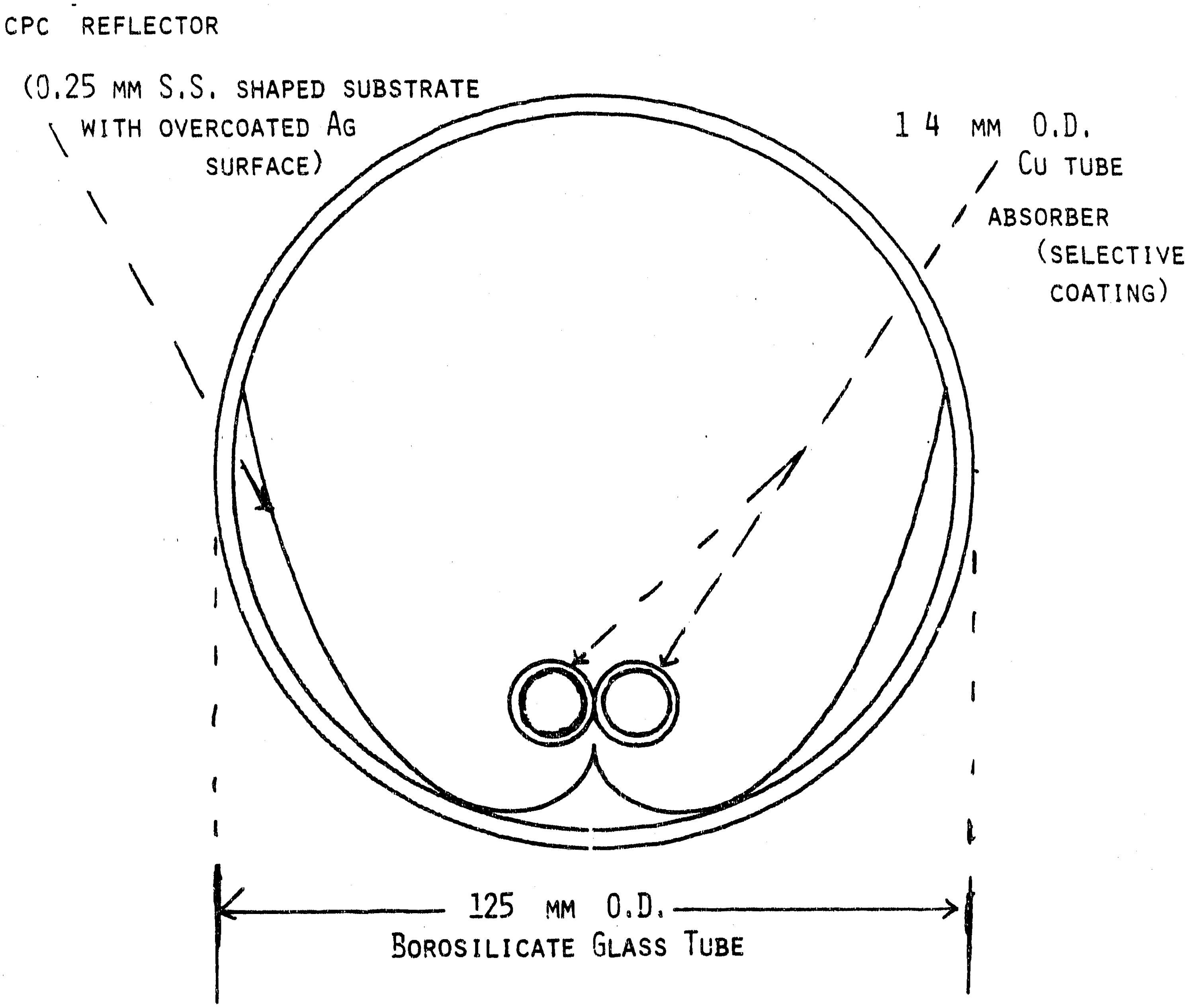

FIGURE 7

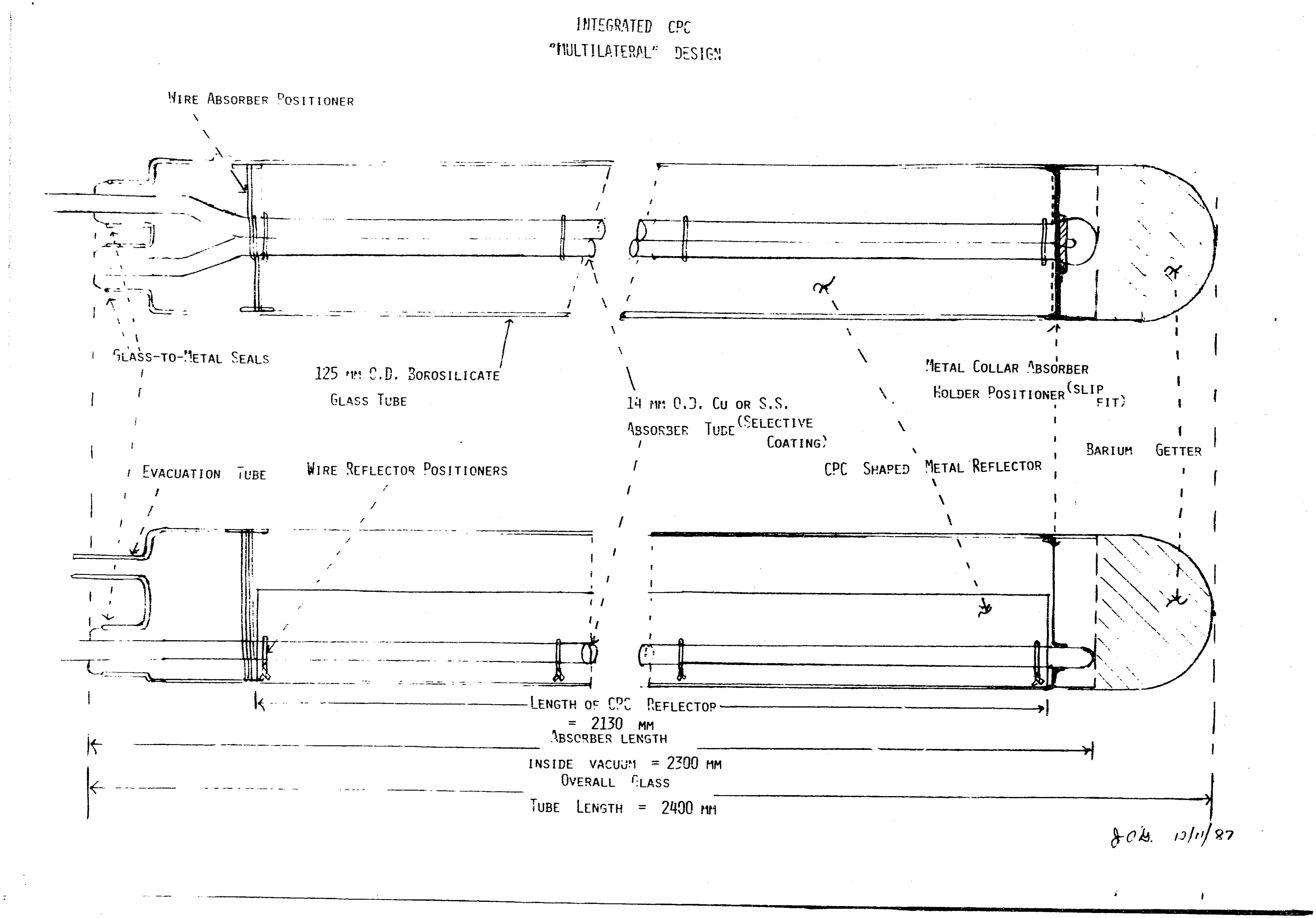
INTEGRATED CPC
"MULTILATERAL" DESIGN
WIRE ABSORBER POSITIONER
GLASS-TO-METAL SEALS
125 MM O.D. BOROSILICATE GLASS TUBE
14 MM O.D. CU OR S.S. ABSORBER TUBE (SELECTIVE COATING)
METAL COLLAR ABSORBER HOLDER POSITIONER (SLIP FIT)
BARIUM GETTER
EVACUATION TUBE
WIRE REFLECTOR POSITIONERS
CPC SHAPED METAL REFLECTOR
LENGTH OF CPC REFLECTOR = 2130 MM
ABSORBER LENGTH
INSIDE VACUUM = 2300 MM
OVERALL GLASS TUBE LENGTH = 2400 MM
JCG. 12/11/87

FIGURE 8

END

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