Abstract

In the field of mechanical fabrication, computer numerical control (CNC) of machine tools has become very mature in the past decade. The same potential exists for optical coating production, but has lagged in time due to the increased number and complexity of the parameters which have to be controlled. In the past few years, it has become possible to purchase CNC optical coating systems with reasonable capability, repeatability, and reliability. This paper reviews the capabilities and status of various CNC coating systems which have been surveyed.

Introduction

In the context of this paper, we are defining the Computer Numerically Controlled Coating Chamber (CNCCC) as an optical coating chamber with the capability to automatically and repeatably produce a variety of optical coatings using optical monitor and crystal termination control without operator intervention between the loading and unloading of the optical parts. A goal for such a machine would ultimately be to produce results (production and/or development) at a lower net cost than manually controlled systems. We here review the requirements, history, experience, availability, cost and probable future of such CNCCC's.

Requirements

Our view of the requirements represents the precision optical instrument business which is heavily influenced by military requirements. We suspect that laboratory and other professionally used optical components have similar requirements, but possibly not as stringent. The largest quantity of optical coating for instrument components is probably still dominated by single layer magnesium fluoride, but high efficiency antireflection coatings of the three or four layer variety have become very widespread and may now dominate. All of the other types of coatings such as reflectors, dichroics, bandpasses, etc. make up representatively smaller quantity requirements in the overall industry, but take up a great deal of effort because of the large variety and greater complexity. Any one coating organization may of course have a great or exclusive concentration in some area such as narrow bandpass filters.

Typical coating operations in the military/aerospace business will have from about 10 to 60 different coating processes that need to be run at least every few months to meet production requirements. Forty (40) or more layer processes are routine at this time, and 200 layers have been mentioned in recent years. The requirements continue to press the state of the art to higher performance in density, transparency, durability, wavelength accuracy, cost, etc.

Historical background

Morton[1] reported on what we believe to be the first major CNCCC work which was producing coatings as early as 1977 at Texas Instruments. They had modified commercially available chambers with computer controls. Many such systems have been put into operation there for their own extensive coating requirements. They have recently received systems from Denton Vacuum which were constructed to their requirements in a cooperative development. They have a system on order from Dynavac Corporation, and they had leased a system from Leybold Heraeus in 1984.

Leybold Heraeus has developed and sold the first commercially available CNCCC's with optical layer thickness control which have been reported by Herrmann, et al.[2,3,4]. We had the opportunity to witness the automatic operation of one of these at Olde Delft in 1983. The first three fully automated Leybold Heraeus A1100's were imported into the United States by the author at Martin Marietta Aerospace in 1984. Since that time, we are aware of three other units in the US at Coherent, Inc., McDonnell Douglas, and the Leybold Heraeus applications laboratory.

At Opto Mechanik, we currently operate a Balzers system without optical layer thickness control but with semi-automatic operation by crystal control. We have had the opportunity to see the GSM 420 which is about to be released and is expected to give Balzers an entry in the CNCCC market as we define it. We are not aware of any of these systems in the field as of early 1986.

Dynavac Corporation delivered its first CNCCC to Itek Corporation in 1985. That system is optical monitor controlled and is reported to be doing principally narrow bandpass filters very successfully to date. They now have another system in the field and several others under construction.

The Eddy Company delivered a CNCCC to Pacific Optical in about 1983.

The Eaton Corporation delivered an automated system to Parks-Jaggers which is an ion cluster beam system in 1984.

Literature from the Showa Shinku Company which we have recently received indicates that they offer an optically controlled CNCCC. As of this writing, we have not had an opportunity to see what they have to offer or what its performance may be.

Gibson et al.[5] have reported work on an automated optical cutoff system and its comparison with a human operator. They show a measurable improvement of the automation over the operator in precision of the passband of narrow filters.

Intellemetrics Ltd. offers an IL500 optical monitor cutoff system which may be capable of being retrofit to existing systems to achieve some portion of the CNCCC requirements. We are currently preparing tests on one of these systems. Similarly, the Balzers GSM 420 might be retrofitable if it is offered separately. Denton, Dyn-Optics, Eddy, and others also offer optical monitors with varying degrees of automatic cutoff capability. The scope of this paper does not allow us to delve further into these subsystems.

Optical and crystal monitoring

We and Morton[1] believe that there is generally an inherent advantage, if not necessity, to control optical coatings by an optical monitor, since it is the optical result that is desired. However, we must acknowledge that much good coating is still done with only a crystal monitor. Thoeni[6] has given an extensive systems analysis of the factors and requirements for process control and automation and of the effects of various errors.

Our coating operators on the BAK760 currently prefer to use the crystal controlled automatic processes over a manually controlled optical cutoff. It is easier and faster because it is automated for crystal layer termination but not automated for optical monitor cutoffs. It should be as easy with an optically controlled automatic process. A dip coating process is another example of the fact that some coatings can be done very successfully without direct optical control. In both that and crystal controlled processes, all parameters must be highly controlled and repeatable for successful coatings with stringent spectral requirements. It appears that new requirements will push beyond what can be done with crystal control only. Measurements which we have made on our current silicon dioxide and titanium dioxide processes indicate a plus or minus variation of 3% and 4% respectively in the optical thickness when the thickness is crystal controlled. The work of Herrmann, Klug, Zoller, and Zultzke[3] lead us to believe that this is comparable with the errors in optical monitoring as practiced to date with turning point cutoff.

Schroedter[11] just reported a new scheme which seems to incorporate the best features of both the optical and crystal monitors. The optical monitor signal level is stored in a computer as a function of crystal monitor thickness in real time. Figure 1 illustrates the principle of the scheme. The data is constantly fit by a "sine" curve of the expected type and the turning point is predicted. As more data points are gathered, the estimated turning point becomes more accurate. Once a turning point is past, the crystal is well calibrated by the optical monitor, and it appears that the crystal can be used for a more accurate trigger point than just an optical monitor. We believe this should lead to improved monitoring in future systems.

Klug, et al.[12] reported a one step process adjustment from the first test run to the designed performance of a six layer broad band antireflection coating using a Leybold Heraeus A1100 CNCCC. An inverse synthesis computer program was used to fit the results of the first run for actual index, dispersion, and thickness. The process program was then adjusted accordingly and the results were as designed. This is a good example of reducing process development time using a CNCCC plus a results analysis program.

Level monitoring at a single wavelength on a single test chip or the actual parts has been described by Macleoud and Pelletier[7] and expanded upon by Zhao[8]. It appears that this approach can be incorporated easily into automated optical monitors and should give results which are an order of magnitude better than turning point monitoring in the region around the monitoring wavelength. However, with level monitoring, the photometric accuracy and particularly the stability of the optical monitor are much more critical than it has been with turning point monitoring. As we understand it, the Leycom/OMS2000 from Leybold heraeus and the GSM 420 from Balzers use a reference detector to sense and correct for changes in source brightness. This can be better than no reference at all, but still can make no correction for detector and other variations. Gibson and Lissberger[9] describe an automated optical monitor with some degree of double beam sophistication. Future systems may require a true double beam spectrophotometer as the optical monitor. Very few optical coating facilities today would use a single beam spectrophotometer to measure their resulting coatings, so it is somewhat incongruous to use something less precise to produce the desired results. Dynavac has gone to some lengths to provide a very stable source and detector system which appears to perform well, but it is only a single beam system with no reference beam.

We have done some preliminary work with level monitoring on the BAK760, but have found some frustrating instabilities in the optical monitor signal levels. We plan to publish some work in this area later this year. We believe that the Leycom software and probably most others are programmed to correct for unexpected photometric levels at the turning points due to absorption, scattering, monochrometer bandwidth effects, etc. and to use this information to determine the cut point after the last turning point. This also will correct to a certain degree for photometric drift in the optical monitor. This practice is probably common in manual, single chip monitoring. We are working to apply this technique with level monitoring on a single chip manually to correct for the limitations of the present monitor as much as practical.

Level monitoring with software corrections for unexpected small changes appear to offer some compensation and good reproducibility in a region around the monitoring wavelength. This probably represents the state of the art in the general precision optical coating industry at this time. However, we believe that the work of Vidal and Pelletier [10] on broadband optical monitoring will be incorporated in the next generation of optical monitoring because of its potential to correct and compensate errors for a broad spectral region. This technique tends to be computationally intensive and requires more computer speed and power than the present techniques; but the computing capabilities available at a reasonable cost seem to be staying ahead of the optical monitor requirements. Work at all of the institutions working on CNCCC's seems to be pushing toward doing more with the computer to improve the results.

Experience to date

We would like to share our experience and what we have learned from our conversations with others who have used CNCCC systems. One lesson which the author learned in the acquisition of the three A1100's for Martin Marietta was to have as the acceptance test a production process which will be used in the chamber after it is accepted. We learned that some purchasers of CNC machining centers accept the systems with the tooling and program which will produce some part that the system will be used to manufacture. This means that the new system can be immediately productive when accepted. We had many months of delay while we learned the differences of the new systems with respect to processes that were routinely run on other manual equipment. Conversations with current users of those systems say that they are routinely running production on a few processes in each system. However, they do not feel it practical to expect one machine to shift often from one process to another of the 30 to 60 that they use. This might be easy from the programming point of view, but not so easy from the process details point of view. It has proved practical for one operator to keep two automated systems working at the same time. The repeatability of the automatic operation is good. The control of E-gun sweep still may require some operator attention from time to time.

It appears that one of the bigger development challenges of CNCCC's is to eliminate any sensitivity to effects of high power/voltage transients which can occur in gas discharges and electron beam gun arcing. If these affect the controls and programs, the automation is defeated. In the tropical seasons of Florida, we have occasional power fluctuations and outages due to electrical storms which cause additional concerns. Electrical maintenance becomes an even larger concern on CNCCC's than older machines because of the additional electronics. A judicious set of spare parts and clear and complete documentation is important to maintain production readiness.

There is some indication that new processes seem to need a few runs even without parameter changes before they settle in and become stable; this is not explained or well understood by those relating it. The programming of the earlier Leybold Heraeus (Leycom II) and Dynavac systems was somewhat cumbersome but later versions are understandably more user friendly. This is typical in most new developments; one first strives to get the required performance and then to do it more easily.

The cost of automated systems

Since a prime consideration of CNCCC's is the cost benefit to be expected, it is important to examine the cost of such automation. The author has been known to say about this and other robotics and automation, "If it pays, it stays; if it don't, it won't" (please allow poetic license in lieu of grammar). Unless the sum of the cost benefits outweighs the sum of the costs of the additional automation, the CNCCC cannot be expected to endure.

We have recently had an opportunity to enter a new market for a particular coating in sufficient volume to justify a dedicated CNCCC for that one product. At the beginning of the acquisition of the three systems for Martin Marietta, we inherited a specification of over 40 pages in length for such a system. The specification spelled out in great detail how the system should be built. It is against the authors principals of management to take that approach. If the resulting system does not perform well or is not the best that the producer could have done, it is the fault of the specifier, not the producer. It is the authors belief that he should specify what the system is to do and what its performance must be and leave the details of how to do it in the expert hands of an experienced coating system producer. To that end, a one page specification was propogated which specified the measurable results which must be achieved and under what conditions. The results of the responses give some representative indication of the costs of a fully automated CNCCC which will perform to the current state of the art requirements.

The requirements called for the ability to deposit minimum specified thicknesses of titanium and silicon dioxides and also magnesium fluoride for other thermal source applications. The uniformity and repeatability requirements were plus or minus 1% in the visible spectrum. Scattering and absorption were limited to 3% in the mid-visible for some fairly thick stacks of TiO2 and SiO2. Four consecutive successful demonstration runs of this coating were required with a cumulative yield of 90% of a chamber full of parts. It was interesting to find that each producer had different concerns in the requirement with little overlap. One was concerned with how to meet the SiO2 thickness requirements. Another was concerned with the probable high scattering in thick layers of SiO2 (might look like milk glass). Still another was concerned about meeting the uniformity and repeatability requirements. None of the producers was willing to commit to the acceptance test requirements. It appears that we have sounded the depths of the state of the art and found that it is not quite as deep as four runs in a row with 90% yield. Figure 2 shows the cost versus chamber size for CNCCC's which are expected to be at the state of the art from various producers who are deemed qualified by the author to deliver such a system. Since these quotations represent four producers in three western countries as of early 1986, the changes in exchange rates could favor different producers as a function of time. It appears that prices are coming down as more producers demonstrate viable CNCCC systems.

We have been somewhat disappointed at the apparent slow progress in commercially available CNCCC systems over the past three or four years. We are now almost ten years from Texas Instruments' beginning efforts in the field.

We might note in passing that optical monitor cut systems for semi-automatic use range from under $10,000 to over $40,000.

Expectations for the future

It appears that Balzers, Denton, Dynavac, and Leybold Heraeus are all committed to some degree to CNCCC offerings that fit our definition. We feel that these producers and Showa Shinku deserve careful watching by those interested in coating automation. This is not to say that others may not now or in the future also deserve such watching. Some of the retrofit packages may also become valuable to those with existing manual cut systems. Level monitoring and later broadband monitoring are expected to have an increasing impact on the quality and reproducibility of optical coatings.

We have not otherwise discussed it, but two other tools seem to be coming into more common use for the benefit of optical coatings. The residual gas analyser (RGA) is being used beneficially for vacuum quality diagnostics and also for more positive control of oxygen partial pressure in reactive depositions. Ion assisted deposition (IAD) seems to have great potential for improved coating density and stoichiometry. We expect to see IAD in broad use over the next five years.

Conclusion

We have reviewed the state of the art in computer numerically controlled coating chambers as we know it in the western hemisphere. There are now several producers of viable systems in this arena. The capabilities are moving beyond the developmental stage, but the confidence level is not yet at a mature stage. Cost and cost benefit will be the prime factor in most organizations' decision to acquire such a system or not. We expect the industry to mature over the next five years by capitalizing on already existing technology.

References

1. Dale E. Morton, "Automation of an optically monitored box coater". presented 30 April 1981, Cherry Hill, New Jersey and "Automated vacuum coater utilizating optical monitoring (A), JOSA 71: 1575 (1981).

2. R. Herrmann and A. Zoller, "Automated control of optical layer fabrication processes", SPIE Proceeding 401, Geneva, (1983).

3. R. Herrmann, W. Klug, A. Zoller, and W. Zultzke, "Automated vacuum-coating plant for IR-optical coatings", Paper ThA-D3, OSA Topical Meeting on Optical Interference Coatings, Monterey, California, (April 1984).

4. R. Herrmann, "Automatisierte Vakuumbeschichtung optischer Bauteile", Feinwerktechnik & Messtechnik, 92, p7-10 (1984)1.

5. D.R. Gibson, P.H. Lissberger, I. Salter, and D.G. Sparks, "A precision adaptation of the 'turning point' method of monitoring the optical thickness of dielectric layers using microprocessors", Optica Acta, 29, p221-234 (1982)2.

6. W.P. Thoeni, "Deposition of optical coatings: process control and automation", Thin Solid Films, 88, p385-397 (1982).

7. H.A. Macleod and E. Pelletier, "Error compensation mechanisms in some thin-film monitoring systems", Opt. Acta 24,907 (1977).

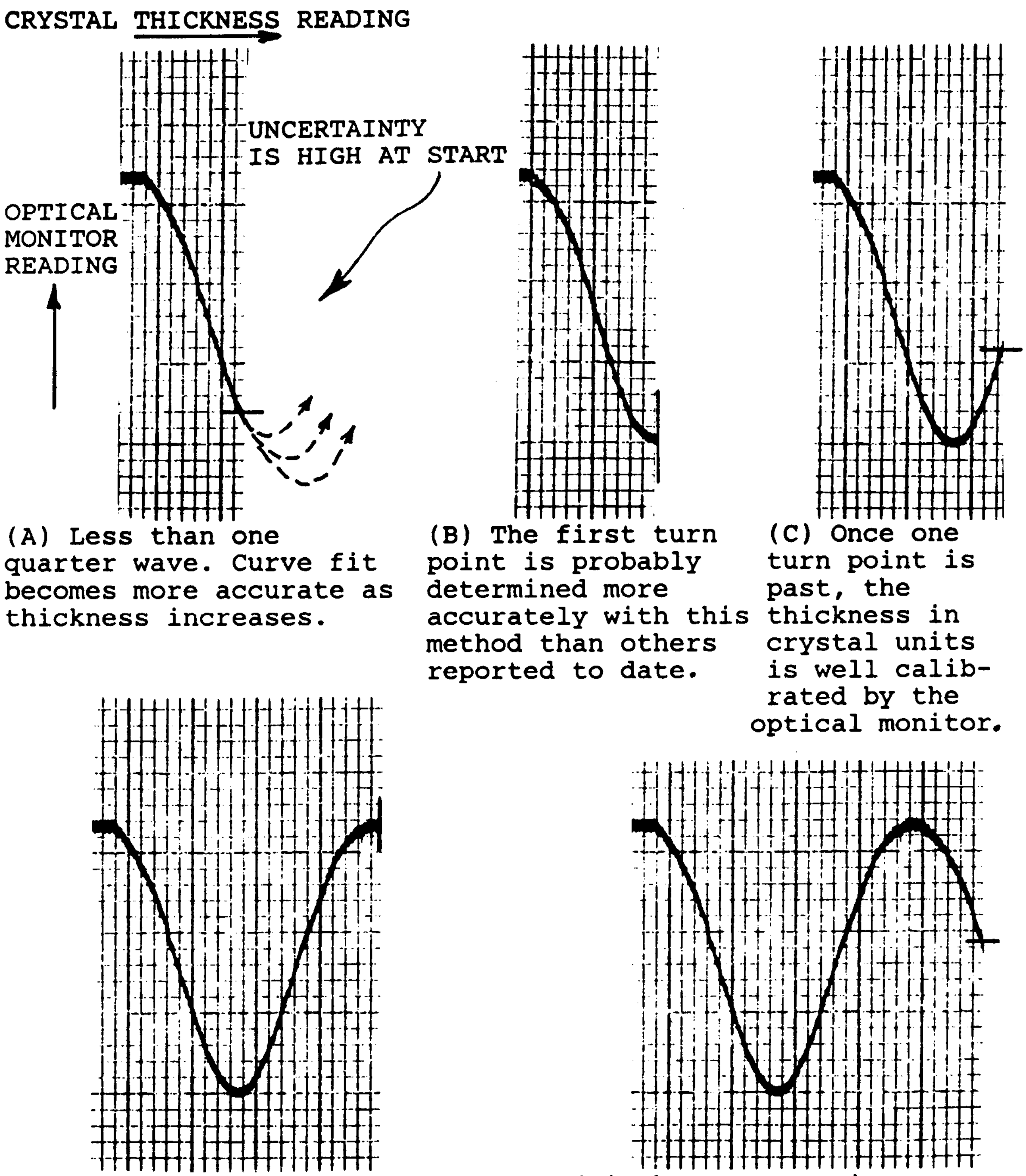
8. F. Zhao, "Monitoring of periodic multilayers by the level method", Applied Optics 24, p3339-3342 (1985).

9 D.R. Gibson and P.H. Lissberger, "Optical properties of narrow-band spectral filter coatings related to layer structure and preparation", Applied Optics 22, p269-281 (1983).

10. B. Vidal and E. Pelletier, "Nonquarterwave multilayer filters: optical monitoring with a minicomputer allowing correction of thickness errors", Applied Optics 18, p3857-3862 (1979).

11. C. Schroedter, "Evaporation monitoring system featuring software trigger points and on-line evaluation of refractive indices", SPIE Proceeding 652, Innsbruck, (1986).

12. W. Klug, M. Boos, R. Herrmann, "Inverse synthesis for analyzing the variations of spectral properties of optical multilayers from different coating runs", SPIE Proceeding 652, Innsbruck, (1986).



(A) Less than one quarter wave. Curve fit becomes more accurate as thickness increases.

(B) The first turn point is probably determined more accurately with this method than others reported to date.

(C) Once one turn point is past, the thickness in crystal units is well calibrated by the optical monitor.

(D) The second and subsequent turning points are determined accurately.

(E) The accuracy increases further as more turning points are past.

FIGURE 1. Crystal readings are calibrated by optical monitor. Computer records OM readings versus crystal readings and fits data to "sine" curve to predict crystal reading at desired optical trigger point (after Schroedter, ref. 11).

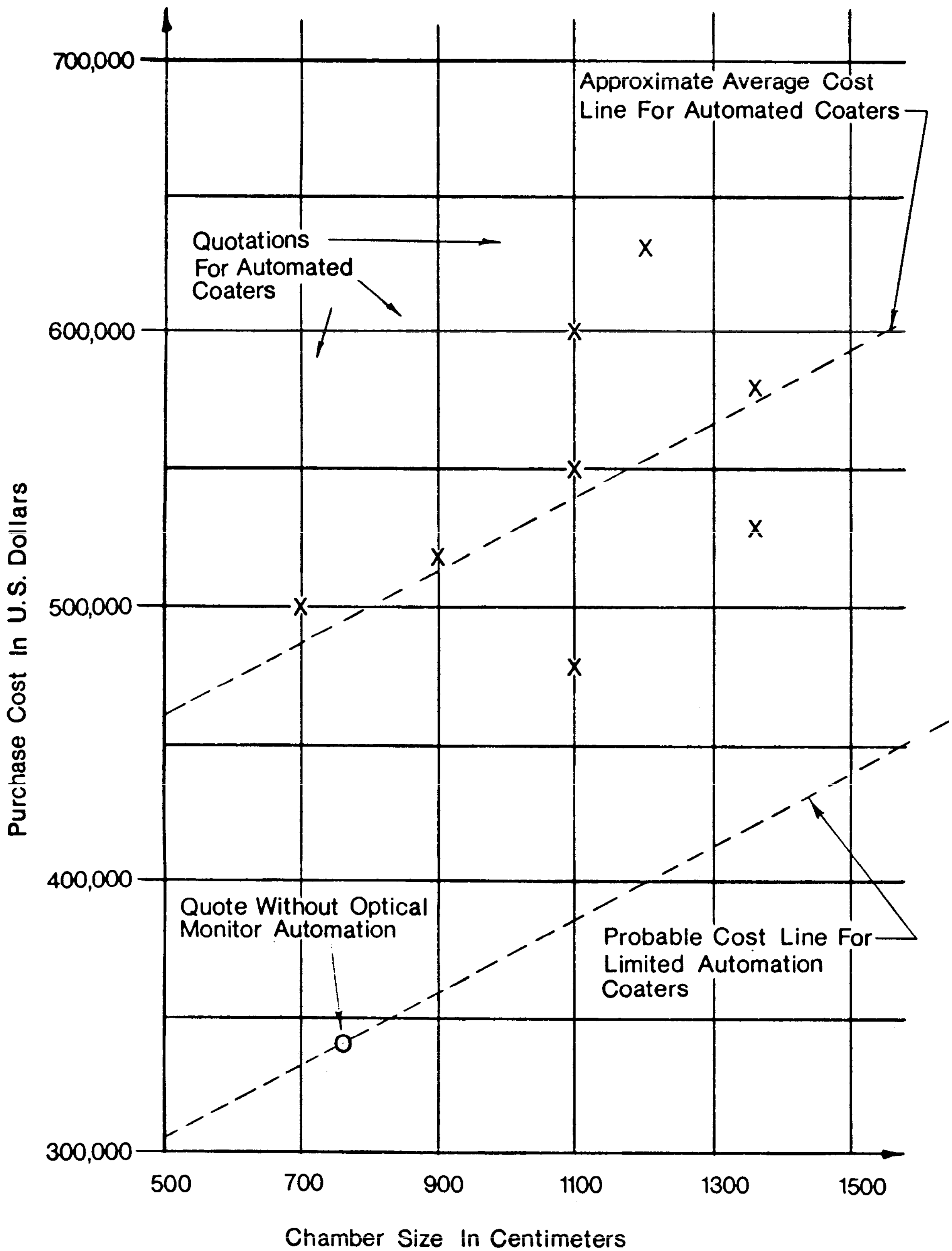


FIGURE 2. Cost versus Size for Automated Coating Chambers