OTIC FILE UUPY

AFWL-TR-87-20

AFWL-TR-87-20



AFWL-TR-87-20

This final report was prepared by the Optical Sciences Center, Tucson, Arizona under Contract F29601-85-C-0057, Job Order 63221C with the Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico. Diane J. Martin (ARBD) was the Laboratory Project Officer-in-Charge.

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely Government-related procurement, the United States Government incurs no responsibility or any obligation whatsoever. The fact that the Government may have formulated or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication, or otherwise in any manner construed, as licensing the holder, or any other person or corporation; or as conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

This report has been authored by a contractor of the United States Government. Accordingly, the United States Government retains a nonexclusive, royalty-free license to publish or reproduce the material contained herein, or allow others to do so, for the United States Government purposes.

This report has been reviewed by the Public Affairs Office and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

If your address has changed, if you wish to be removed from our mailing list, or if your organization no longer employs the addressee, please notify AFWL/ARBD, Kirtland Air Force Base, NM 87117-6008 to help us maintain a current mailing list.

This report has been reviewed and is approved for publication.

DIANE J. MARTIN Project Officer

GARY L. DUKE Major, USAF Ch, Optical Components Branch

FOR THE COMMANDER

JAMES A. HORKOVICH Lieutenant Colonel, USAF Ch, SDI Laser Technology Office

DO NOT RETURN COPIES OF THIS REPORT UNLESS CONTRACTUAL OBLIGATIONS OR NOTICE ON A SPECIFIC DOCUMENT REQUIRES THAT IT BE RETURNED.

| UN | ICL | AS | SI | F | I | ED | | | |
|-----|------|----|-----|-----|----|-------|-----|------|-----|
| CEC | DITY | 1 | ACC | 101 | ζ. | TION! | OF. | THIS | DAG |

| 15 REPORT SECURITY CLASSIFICATION Ib RESTRICTUE WARKINGS Unclassified 25 SECURITY CLASSIFICATION AUFHORITY 20 DISTRIBUTION (XAVALABULTY OF REPORT 25 DECLASSIFICATION / DOWNGRADING SCHEDULE Unlimited. Initiation Unlimited. 26 DECLASSIFICATION / DOWNGRADING SCHEDULE Unlimited. SMONTORING ORGANIZATION REPORT NUMBER(S) 26 ANAME OF PERFORMING ORGANIZATION REPORT NUMBER(S) S MONTORING ORGANIZATION REPORT NUMBER(S) 26 ANAME OF PERFORMING ORGANIZATION S0 OFFICE SYMBOL 24 NAME OF MONTORING ORGANIZATION 27 ANAME OF PERFORMING ORGANIZATION S0 OFFICE SYMBOL 75 ADDRESS (CIP, State, and ZIP Code) 20 MILSON OF SECOND B0 OFFICE SYMBOL 75 ADDRESS (CIP, State, and ZIP Code) 21 ADDRESS (CIP, State, and ZIP Code) 75 ADDRESS (CIP, State, and ZIP Code) 76 22 DAGRESS (CIP, State, and ZIP Code) 76 SOURCE OF FUNDING NUMBERS 775 23 ADDRESS (CIP, State, and ZIP Code) 76 SOURCE OF FUNDING NUMBERS 24 ADDRESS (CI | Unclassified 2a. SECURITY CLASSIFICATION AUTHORITY 2b. DECLASSIFICATION / DOWNGRADING SCHE 4. PERFORMING ORGANIZATION REPORT NUM 6a. NAME OF PERFORMING ORGANIZATION Optical Sciences Center 6c. ADDRESS (City, State, and ZIP Code) University of Arizona Tucson, AZ 85721 8a. NAME OF FUNDING / SPONSORING ORGANIZATION - 8c. ADDRESS (City, State, and ZIP Code) 11. TITLE (Include Security Classification) EFFECT OF THERMAL CYCLING 12. PERSONAL AUTHOR(S) Stephen F. Jacobs | MBER(S) 6b. OFFICE SYMBOL (If applicable) 8b. OFFICE SYMBOL | 3. DISTRIBUTION Approved unlimited 5. MONITORING AFWL-TR-8 7a. NAME OF M Air Force 7b ADDRESS (CI Kirtland 9 PROCUREMEN | V/AVAILABILITY for public ORGANIZATION 7-20 NONITORING ORG Weapons Li ity, State, and Z AFB, NM 87 | release; c REPORT NUME GANIZATION aboratory | · · · · • | | |
|---|--|---|---|---|--|--|--|--|
| 22. SECURITY CLASSIFICATION AUTHORITY 1 SOFRIBUTION, AVAILABILITY OF REPORT 22. SECURITY CLASSIFICATION AUTHORITY 1 SOFRIBUTION, AVAILABILITY OF REPORT 23. DECLASSIFICATION / DOWNGRADING SCHEDULE Inimited. Approved for public release; distribution 24. DECLASSIFICATION / DOWNGRADING SCHEDULE Inimited. Inimited. 24. FREFORMING ORGANIZATION REPORT NUMBER(S) AFRH-TR-87-20 25. NAME OF PERFORMING ORGANIZATION REPORT NUMBER(S) AFRH-TR-87-20 26. NAME OF PERFORMING ORGANIZATION REPORT NUMBER(S) AFRH-TR-87-20 26. NAME OF PERFORMING ORGANIZATION REPORT NUMBER(S) AFRH-TR-87-20 27. NAME OF PENFORMING ORGANIZATION So OFFICE SYMBOL (If applicable) 7b ADORESS(CIP, State, and ZIP Code) 27. DISTRIBUTION / AVAILABILITY OF REPORT TASK Kirtland AFB, NM 87117-6008 28. ADDRESS(CIP, State, and ZIP Code) It SOURCE OF FUNDING NUMBERS PROCLARMENT INSTRUMENT IDENTIFICATION NUMBER 28. ADDRESS(CIP, State, and ZIP Code) It SOURCE OF FUNDING NUMBERS PROCLARMENT NO. SoCOFT 29. DREEDORT Stephen F. JacODS ISS OFFICE SYMBOL 9 PROCLARMENT INSTRUMENT IDENTIFICATION NUMBER 29. THE OF REPORT TISS THE OFFICE SYMBOL 10 PROFECE SYMBOL SocOFT 29 | 2a. SECURITY CLASSIFICATION AUTHORITY 2b. DECLASSIFICATION / DOWNGRADING SCHE 4. PERFORMING ORGANIZATION REPORT NUM 6a. NAME OF PERFORMING ORGANIZATION Optical Sciences Center 6c. ADDRESS (City, State, and ZIP Code) University of Arizona Tucson, AZ 85721 8a. NAME OF FUNDING / SPONSORING ORGANIZATION - 8c. ADDRESS (City, State, and ZIP Code) 11. TITLE (Include Security Classification) EFFECT OF THERMAL CYCLING 12. PERSONAL AUTHOR(S) Stephen F. Jacobs | MBER(S) 6b. OFFICE SYMBOL (If applicable) 8b. OFFICE SYMBOL | Approved unlimited 5. MONITORING AFWL-TR-8 7a. NAME OF M Air Force 7b ADDRESS (C Kirtland 9 PROCUREMEN | for public ORGANIZATION 7-20 NONITORING ORG Weapons Li ity, State, and Z AFB, NM 87 | release; c REPORT NUME GANIZATION aboratory | · · · · • | | |
| A PERFORMING ORGANIZATION / DOWNGRADING SCHEDULE A PERFORMING ORGANIZATION REPORT NUMBER(S) A DOPTOVED for Dublic release; distribution unlimited. 4 PERFORMING ORGANIZATION REPORT NUMBER(S) S. MONIFORMO ORGANIZATION REPORT NUMBER(S) S. MONIFORMO ORGANIZATION REPORT NUMBER(S) 6a. NAME OF PERFORMING ORGANIZATION 6b. OFFICE SYMBOL (H applicable) 7b. NAME OF MONIFORING ORGANIZATION 6c. ADDRESS (CIP, State. and ZIP Code) 7b. ADDRESS (CIP, State. and ZIP Code) 7b. ADDRESS (CIP, State. and ZIP Code) 0 Iniversity of Arizon 7b. OFFICE SYMBOL (H applicable) 7b. POCUREMENT INSTRUMENT IDENTIFICATION NUMBER F29601-85-C-0057 8c. ADDRESS (CIP, State. and ZIP Code) 10. SUPECE OF FUNDING NUMBERS PROGRAM 10. SUPECE OF FUNDING NUMBERS PROGRAM WORK UNIT ROW COST 8c. ADDRESS (CIP, State. and ZIP Code) 10. SUPECE OF FUNDING NUMBERS PROGRAM 10. SUPECE OF FUNDING NUMBERS PROGRAM WORK UNIT 11. TITLE (Include Security Classification) 11b. TIME COVERED FROM APP 85 to Jan 87 14. DATE OF REPORT (Year, Month, Day) 15. PAGE COUNT 12. PERSONAL AUTHOR(S) SUB-GROUP 11a. SUBJECT TERMS (Continue on reverse if incettary and identify by block number) 12. SUBJECT TERMS (Continue on reverse if necetary and identify by block number) 12. SUBJECT TERMS (Continue on reverse if necetary and identify by block number) 13. SUBJECT TERMS (Continue on reverse if necetary and identify by blo | 2b. DECLASSIFICATION / DOWNGRADING SCHE 4. PERFORMING ORGANIZATION REPORT NUM 6a. NAME OF PERFORMING ORGANIZATION Optical Sciences Center 6c. ADDRESS (City, State, and ZIP Code) University of Arizona Tucson, AZ 85721 8a. NAME OF FUNDING / SPONSORING ORGANIZATION - 8c. ADDRESS (City, State, and ZIP Code) 11. TITLE (Include Security Classification) EFFECT OF THERMAL CYCLING 12. PERSONAL AUTHOR(S) Stephen F. Jacobs | MBER(S) 6b. OFFICE SYMBOL (If applicable) 8b. OFFICE SYMBOL | Approved unlimited 5. MONITORING AFWL-TR-8 7a. NAME OF M Air Force 7b ADDRESS (C Kirtland 9 PROCUREMEN | for public ORGANIZATION 7-20 NONITORING ORG Weapons Li ity, State, and Z AFB, NM 87 | release; c REPORT NUME GANIZATION aboratory | · · · · • | | |
| AFWL-TR-87-20 Ga. NAME OF PERFORMING ORGANIZATION Optical Sciences Center Sb. OFFICE SYMBOL (If applicable) 7a. NAME OF MONITORING ORGANIZATION Air Force Weapons Laboratory Ge. ADDRESS (Gry, Size, and ZIP Code) To ADDRESS (Gry, Size, and ZIP Code) To ADDRESS (Gry, Size, and ZIP Code) University of Arizona Tucson, AZ 55721 Sb. OFFICE SYMBOL (If applicable) 9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER F29501-85-C-0057 Ba. NAME OF FUNDING 'SPONSORING ORGANIZATION | 6a. NAME OF PERFORMING ORGANIZATION Optical Sciences Center 6c. ADDRESS (City, State, and ZIP Code) University of Arizona Tucson, AZ 85721 8a. NAME OF FUNDING / SPONSORING ORGANIZATION 8c. ADDRESS (City, State, and ZIP Code) 11. TITLE (Include Security Classification) EFFECT OF THERMAL CYCLING 12. PERSONAL AUTHOR(S) Stephen F. Jacobs | 6b. OFFICE SYMBOL (If applicable) 8b. OFFICE SYMBOL | AFWL-TR-8 7a. NAME OF M Air Force 7b ADDRESS (C Kirtland 9 PROCUREMEN | 7-20 IONITORING ORI Weapons La ity, State, and 2 AFB, NM 87 | GANIZATION aboratory <i>IP Code</i>) | BER(S) | | |
| AFWL-TR-87-20 AFWL-TR-87-20 AFWL-TR-87-20 AFWL-TR-87-20 AFWL-TR-87-20 Ta NAME OF PERFORMING ORGANIZATION Optical Sciences Center C(# applicable) Air Force Weapons Laboratory K: ADDRESS (Ciry, State, and ZIP Code) University of Arizona Uuscon, AZ 65721 La NAME OF FUNDING/SPONSORING ORGANIZATION ORGANIZATION COGANIZATION COGANIZAT | 5a. NAME OF PERFORMING ORGANIZATION Optical Sciences Center 5c. ADDRESS (Gity, State, and ZIP Code) University of Arizona Tucson, AZ 85721 3a. NAME OF FUNDING / SPONSORING ORGANIZATION | 6b. OFFICE SYMBOL (If applicable) 8b. OFFICE SYMBOL | AFWL-TR-8 7a. NAME OF M Air Force 7b ADDRESS (C Kirtland 9 PROCUREMEN | 7-20 IONITORING ORI Weapons La ity, State, and 2 AFB, NM 87 | GANIZATION aboratory <i>IP Code</i>) | SER(S) | | |
| Se. NAME OF PERFORMING ORGANIZATION Optical Sciences Center Bb. OFFICE SYMBOL (If applicable) 7a. NAME OF MONITORING ORGANIZATION Air Force Weapons Laboratory Sc. ADDRESS (City, State, and ZIP Code) Name OF FUNDING (Sponsoring Uncson, AZ 85721 Name OF FUNDING (Sponsoring ORGANIZATION Sname OF FUNDING (SPONSORING ORGANIZATION Bb. OFFICE SYMBOL (If applicable) 9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER F29601-85-C-0057 Name OF FUNDING (Sponsoring Organization) Bb. OFFICE SYMBOL (If applicable) 9 PROCURE OF FUNDING NUMBERS PROGRET No. Stack WORK UNIT NO. Stack 1. TITLE (Include Security Classification) ID. SOURCE OF FUNDING NUMBERS PROGRET No. Stack NORECT No. Stack WORK UNIT NO. Stack 2. PRESONAL AUTHOR(I) Stephen F. Jacobs ID. STACK COVERED Stephen F. Jacobs ID. SOURCE OF REPORT PROM Apr 85 TO Jan 87 ID. DATE OF REPORT (Year, Month, Day) IS PAGE COUNT S2 7. COSATI CODES IB. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) The objective of this effort is to evaluate the stability of low expansion Zerodur, devel materials. Name charges, Low expansion materials 7. ADDRESS (Continue on reverse if necessary and identify by block number) ID. WEADSTICE TERMS (Continue on reverse if necessary and identify by block number) 7. ELO GROUP IB. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) ID. MELO SUPPERONT 7. ELO GROUP </td <td>Optical Sciences Center Sc. ADDRESS (Gity, State, and ZIP Code) University of Arizona Tucson, AZ 85721 Ba. NAME OF FUNDING / SPONSORING ORGANIZATION </td> <td>(If applicable) 8b. OFFICE SYMBOL</td> <td>7a NAME OF N Air Force 7b ADDRESS (C Kirtland 9 PROCUREMEN</td> <td>ionitoring or Weapons La ity, State, and Z AFB, NM 87</td> <td>aboratory [P Code]</td> <td></td> | Optical Sciences Center Sc. ADDRESS (Gity, State, and ZIP Code) University of Arizona Tucson, AZ 85721 Ba. NAME OF FUNDING / SPONSORING ORGANIZATION | (If applicable) 8b. OFFICE SYMBOL | 7a NAME OF N Air Force 7b ADDRESS (C Kirtland 9 PROCUREMEN | ionitoring or Weapons La ity, State, and Z AFB, NM 87 | aboratory [P Code] | | | |
| Optical Sciences Center (if applicable) Air Force Weapons Laboratory Sc. ADDRESS (City, State, and ZIP Code) To ADDRESS (City, State, and ZIP Code) Kirtland AFB, NM 87117-6008 University of Arizona B. OFFICE SYMBOL (if applicable) PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER F29601-85-C-0057 Kc. ADDRESS (City, State, and ZIP Code) B. OFFICE SYMBOL (if applicable) PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER F29601-85-C-0057 Kc. ADDRESS (City, State, and ZIP Code) To. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. SUPPLEMENT NO. Stephen F. Jacobs MORK UNIT ACCESSION Stephen F. Jacobs 32, FYRE OF AREORT Final Tab. TIME COVERED FROM Apr 85 To An 87 Task Now ACCESSION Stephen F. Jacobs 34, STRECT CONTINUE ON SUB-CROUP Final Tab. TIME COVERED FROM Apr 85 To An 87 Task Now ACCESSION Stephen F. Jacobs 34, TEED GROUP Final Tab. TIME COVERED FROM Apr 85 Ta 87 Stephen F. Jacobs 34, TEED GROUP Final Tab. TIME COVERED FROM Apr 85 Tab. TIME COVERED FROM Apr 85 Stephen F. Jacobs 7 COSATI CODES Tab. TIME COVERED FROM Apr 85 Tab. TIME COVERED FROM Apr 85 Stephen F. Jacobs 7 COSATI CODES Tab. TIME COVERED FROM Apr 85 Tab. TIME COVERED FROM Apr 85 Stephen F. Jacobs 7 COSATI CO | Optical Sciences Center Sc. ADDRESS (Gity, State, and ZIP Code) University of Arizona Tucson, AZ 85721 Ba. NAME OF FUNDING / SPONSORING ORGANIZATION | (If applicable) 8b. OFFICE SYMBOL | Air Force 75 ADDRESS(C Kirtland 9 PROCUREMEN | Weapons La ity, State, and 2 AFB, NM 87 | aboratory [P Code] | | | |
| Sc. ADDRESS (GR), State, and ZIP Code) 75 ADDRESS (GR), State, and ZIP Code) University of Arizona Tucson, AZ 85721 Kirtland AFB, NM 87117-6008 Sa. NAME OF FUNDING/SPONSORING ORGANIZATION 8b. OFFICE SYMBOL (If applicable) 9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER F29601-85-C-0057 K. ADDRESS (GR), State, and ZIP Code) 10. SOURCE OF FUNDING NUMBERS PROGRAM INSTRUMENT IDENTIFICATION NUMBER F29601-85-C-0057 K. ADDRESS (GR), State, and ZIP Code) 10. SOURCE OF FUNDING NUMBERS PROGRAM INSTRUMENT IDENTIFICATION NUMBER F29601-85-C-0057 K. ADDRESS (GR), State, and ZIP Code) 10. SOURCE OF FUNDING NUMBERS PROGRAM INSTRUMENT IDENTIFICATION NUMBER F29601-85-C-0057 1. TITLE (Include Security Classification) EFFECT OF FUNDING NUMBERS FROM AD P 85 PROGRAM 2. PERSONAL AUTHOR(3) 2. PERSONAL AUTHOR(3) 30 3. Supplement F. Jacobs 13. TIME COVERED TROM ADP 85 14. DATE OF REPORT TASK New York NO. Supplement P. Jacobs 7. COSATI CODES 13. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) 15. PAGE COUNT 52 7. COSATI CODES 13. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) 15. Page changes, Low expansion materials (Sontrue on reverse if necessary and identify by block number) 7. COSATI CODES 13. SUBJECT TERMS (Continue on reverse if necessary and identify | SC ADDRESS (City, State, and ZIP Code) University of Arizona Tucson, AZ 85721 Ba. NAME OF FUNDING/SPONSORING ORGANIZATION | | 76 ADDRESS(G Kirtland 9 PROCUREMEN | ity, State, and Z AFB, NM 87 | IP Code) | | | |
| University of Arizona Tucson, AZ 85721 Kirtland AFB, NM 87117-6008 a. NAME OF FUNDING YEARSON AND (If applicable) ONGANIZATION Bb. OFFICE SYMBOL (If applicable) 9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER F29601-85-C-0057 k. ADDRESS (City, State, and ZIP Code) 10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. 63221C Task NO ACCESSION 31 1. TITLE (Include Security Classification) PROCE EFFECT OF THERMAL CYCLING PROGRAM ESEMPTINO. 532CPhen F. Jacobs 2. PERSONAL AUTHOR(3) Stephen F. Jacobs 13b. TIME COVERED FROM Apr 85 TO Jan 87 1988, May 7. COSATI CODES Final 11b. TIME COVERED FROM Apr 85 TO Jan 87 1988, May 7. COSATI CODES Final 11b. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) Thermal expansion coefficient, Hysteresis, Mirror substra materials, Thermal properties, Surface figure changes, Low expansion materials of high energy laser materials on the time weaption materials of high energy laser metrials Zerodur, ULE, and Cer-Vit as possible substrate materials for high energy laser mirrors. This effort will determine whether there is instability in developmental Zerodur ULE and Cer-Vit over operating temperatures and coating temperatures (300-475K). Zerodur has already been shown to exhibit instability. Thermal cycling will be investigated as a possible approach to eliminate or reduce hysteresis. The effect of polishing on hysteres will also be investigated. 220. DISTRIBUTION/AVALLABULTY OF ABSTRACT DIMELOS/BEL NDIVIOLAL DIMELOS/BEL NDIVIOLAL DEFORM 1473, 34 MAR 83 APR exton may be wed writerhauted. SECURITY CLASSIFICATION | University of Arizona Tucson, AZ 85721 Na. NAME OF FUNDING/SPONSORING ORGANIZATION K. ADDRESS (City, State, and ZIP Code) 1. TITLE (Include Security Classification) EFFECT OF THERMAL CYCLING 2. PERSONAL AUTHOR(S) Stephen F. Jacobs | | Kirtland 9 PROCUREMEN | AFB, NM 87 | | | | |
| Tucson, ÅZ 85721 Ja, NAME OF FUNDING SPONSORING ORGANZATION Bb. OFFICE SYMBOL (If applicable) 9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER F29601-85-C-0057 kc. ADDRESS (Ciry, State, and ZIP Code) 10. SOURCE OF FUNDING NUMBERS PROJECT Instrument IDENTIFICATION NUMBER F29601-85-C-0057 kc. ADDRESS (Ciry, State, and ZIP Code) 10. SOURCE OF FUNDING NUMBERS PROJECT Instrument IDENTIFICATION NUMBER F2001-85-C-0057 1. TITLE (Include Security Classification) EEFECT OF THERMAL CYCLING Instrument IDENTIFICATION Stephen F. Jacobs 2. PRESONAL AUTHOR(S) Stephen F. Jacobs Instrument IDENTIFICATION FINAL Instrument IDENTIFICATION IS SUPPLEMENTARY NOTATION 7. COSATI CODES Is. TIME COVERED IS. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) Instrument IDENTIFICATION 7. COSATI CODES Is. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) Internal expansion coefficient, Hysteresis, Mirror substre materials, Thermal properties, Surface figure changes, Low expansion materials 7. COSATI CODES Is. Subject TERMS (Continue on reverse if necessary and identify by block number) 7. COSATI CoDES Is. Subject TERMS (Continue on reverse if necessary and identify by block number) 7. COSATI CODES Is. Subject TERMS (Continue on reverse if necessary and identify by block number) 7. Dis effort will determine whethe | TUCSON, AZ 85721 Ba. NAME OF FUNDING/SPONSORING ORGANIZATION | | 9 PROCUREMEN | | 117-6008 | | | |
| ORGANIZATION (if applicable) F29601-85-C-0057 C. ADDRESS (City, State, and ZIP Code) 10. SOURCE OF FUNDING NUMBERS WORK UNIT ELEMENT NO. C. ADDRESS (City, State, and ZIP Code) 10. SOURCE OF FUNDING NUMBERS No. EFFECT OF THERMAL CYCLING 31. 30 2. PERSONAL AUTHOR(S) Stephen F. Jacobs 3a, TYPE OF REPORT 13b. TIME COVERED Final 13b. TIME COVERED 7. COSATI CODES 14. DATE OF REPORT 13b. TIME COVERED 7. COSATI CODES 14. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) 7. COSATI CODES 14. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) 7. COSATI CODES 14. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) 7. COSATI CODES 14. ADATE OF GROWN TO exit on reverse if necessary and identify by block number) 7. COSATI CODES 14. ADATE Continue on reverse if necessary and identify by block number) 7. COSATI CODES 14. ADATE TERMS (Continue on reverse if necessary and identify by block number) 7. COSATI CODES | ORGANIZATION C. ADDRESS (City, State, and ZIP Code) 1. TITLE (Include Security Classification) EFFECT OF THERMAL CYCLING 2. PERSONAL AUTHOR(S) Stephen F. Jacobs | | | T INSTRUMENT | | | | |
| K: ADDRESS (City, State, and ZIP Code) F29601-85-C-00057 K: ADDRESS (City, State, and ZIP Code) ID. SOURCE OF FUNDING NUMBERS PROBAM PROBAM PROBAM PROBAM ELEMENT NO. NO. 63221C SBL1 31 30 1. TITLE (Include Security Classification) EFFECT OF THERMAL CYCLING 2. PERSONAL AUTHOR(5) Stephen F. Jacobs 3a. TYPE OF REPORT Final Thermal expansion coefficient, Hysteresis, Mirror substrate 7. COSATI CODES Field GROUP SUB-GROUP Thermal expansion coefficient, Hysteresis, Mirror substrate Thermal expansion coefficient, Hysteresis, Mirror substrate The objective of this effort is to evaluate the stability of low expansion Zerodur, devel mental Zerodur, ULE, and Cer-Vit as possible substrate materials for high energy laser mirrors. This effort will determine whether there is instability in developmental Zerodu Nos already been shown to exhibit instability. Thermal cycling will be investigated as a costig temperatures (300-475K). Zerodu Nos already been shown to exhibit instability. Thermal cycling will be investigated as a costig tephonature developmental Zerodu N | L. ADDRESS (City, State, and ZIP Code) 1. TITLE (Include Security Classification) EFFECT OF THERMAL CYCLING 2. PERSONAL AUTHOR(S) Stephen F. Jacobs | (if applicable) | F29601-85 | | IDENTIFICATION | NUMBER | | |
| PROGRAM ELEMENT NO. 63221C PROJECT NO. SBL1 TASK NO. SBL1 WORK UNINACCESSION ACCESSION 31 1. TITLE (Include Security Classification) EFFECT OF THERMAL CYCLING 31 30 2. PERSONAL AUTHOR(S) Stephen F. Jacobs 31 30 31 30 3. TYPE OF REPORT Final 13b. TIME COVERED FROM Apr 85 14. DATE OF REPORT (Year, Month, Day) 15. PAGE COUNT 52 6. SUPPLEMENTARY NOTATION FROM Apr 85 To Jan 87 14. DATE OF REPORT (Year, Month, Day) 15. PAGE COUNT 52 7. COSATI CODES 18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) 52 7. COSATI CODES 18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) 52 7. COSATI CODES 18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) 52 7. COSATI CODES 18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) 52 7. COSATI CODES 18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) 52 7. COSATI CODES 18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) 52 7. COSATI CODES 18. SUBJECT TERMS (Continue on re | 1. TITLE (Include Security Classification) EFFECT OF THERMAL CYCLING 2. PERSONAL AUTHOR(S) Stephen F. Jacobs | <u> </u> | 1 | F29601-85-C-0057 | | | | |
| PROGRAM ELEMENT NO. 63221C PROF NO. SBL1 TASK NO. SBL1 WORK UNINACTION ACCESSION 31 11. TITLE (Include Security Classification) EFFECT OF THERMAL CYCLING 31 30 22. PERSONAL AUTHOR(S) Stephen F. Jacobs 31 30 33. TYPE OF REPORT 13b. TIME COVERED FROM Apr 85 14. DATE OF REPORT (Year, Month, Day) 15. PAGE COUNT 52 36. SUPPLEMENTARY NOTATION 13b. TIME COVERED FROM Apr 85 14. DATE OF REPORT (Year, Month, Day) 15. PAGE COUNT 52 16. SUPPLEMENTARY NOTATION 18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) 52 17. COSATI CODES 18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) 15. PAGE COUNT 52 18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) 15. PAGE COUNT 52 19. Defective of this effort is to evaluate the stability of low expansion Zerodur, devel mental Zerodur, ULE, and Cer-Vit as possible substrate materials for high energy laser mirrors. This effort will determine whether there is instability in developmental Zerodur, ULE and Cer-Vit over operating temperatures and coating temperatures (300-475K). Zerodur has already been shown to exhibit instability. Thermal cycling will be investigated as a possible approach to eliminate or reduce hysteresis. The effect of polishing on hysteres will also be investigated. 20. DISTRIBUTION / AVAILABILITY OF ABSTRACT | EFFECT OF THERMAL CYCLING 2 PERSONAL AUTHOR(S) Stephen F. Jacobs | | 10. SOURCE OF | FUNDING NUME | BERS | | | |
| 63221C SBL1 31 30 1. TITLE (Include Security Classification) EFFECT OF THERMAL CYCLING 2. PERSONAL AUTHOR(S) Stephen F. Jacobs 3. TYPE OF REPORT 13b. TIME COVERED Final 13b. TIME COVERED 13b. TIME COVERED 15b. TAGE COUNT 15c. COSATI CODES 11b. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) 7. 15b. TAGE COUNT 16b. SUB-GROUP Thermal expansion coefficient, Hysteresis, Mirror substrate materials . 15b. TAGE Continue on reverse if necessary and identify by block number) The objective of this effort is to evaluate the stability of low expansion Zerodur, devel mental Zerodur, ULE, and Cer-Vit as possible substrate materials for high energy laser mirrors. This effort will determine whether there is instability in developmental Zerodu ULE and Cer-Vit over operating temperatures and coating temperatures (300-475K). Zerodu 12b. TRIBUTION/AV | EFFECT OF THERMAL CYCLING 2 PERSONAL AUTHOR(S) Stephen F. Jacobs | | PROGRAM | PROJECT | TASK | WORK UNIT | | |
| 1. TITLE (Include Security Classification) EFFECT OF THERMAL CYCLING 2. PERSONAL AUTHOR(S) Stephen F. Jacobs 3. TYPE OF REPORT 13b. TIME COVERED Final 13b. TIME COVERED Final 13b. TIME COVERED Final 13b. TIME COVERED Final 13b. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) 7. COSATI CODES 18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) 7. COSATI CODES 18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) 7. COSATI CODES 18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) 7. COSATI CODES 1. HELD GROUP Thermal expansion materials . (1-1-1-1) 1. OW expansion materials . (1-1-1) 1. OW expansion materials . (1-1-1) 1. OW expansion materials for high energy laser mirrors. This effort will determine whether there is instability in developmental Zerodu ULE and Cer-Vit over operating temperatures and coating temperatures (300-475K). <td>EFFECT OF THERMAL CYCLING 2 PERSONAL AUTHOR(S) Stephen F. Jacobs</td> <td></td> <td></td> <td></td> <td></td> <td></td> | EFFECT OF THERMAL CYCLING 2 PERSONAL AUTHOR(S) Stephen F. Jacobs | | | | | | | |
| 2. PERSONAL AUTHOR(S) Stephen F. Jacobs 3a, TYPE OF REPORT Final 13b. TIME COVERED Final 6. SUPPLEMENTARY NOTATION 7. COSATI CODES 18. SUPPLEMENTARY NOTATION 7. COSATI CODES 1988, May 7. COSATI CODES 1988, May 7. COSATI CODES 118. SUPPLEMENTARY NOTATION 7. Intermal Properties 7. Intermal Properties 7. Intermal Propertie | 2. PERSONAL AUTHOR(S) Stephen F. Jacobs | · · · · · · · · · · · · | | | | | | |
| Stephen F. Jacobs Ja, TYPE OF REPORT Final 13b. TIME COVERED FROM ADP 85 To Jan 87 1988, May 7. COSATI CODES 118. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) 7. COSATI CODES 118. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) 7. COSATI CODES 118. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) 7. COSATI CODES 118. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) 7. COSATI CODES 118. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) 7. Low expansion materials 7. Low exponsion to exhibit instability in developmental | Stephen F. Jacobs | / | and the second se | | | * | | |
| Ba TYPE OF REPORT 13b. TIME COVERED FROM Apr 85 To Jan 87 14. DATE OF REPORT (Year, Month, Day) 15. PAGE COUNT 52 6. SUPPLEMENTARY NOTATION 52 52 7. COSATI CODES 18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) 7. COSATI CODES 18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) 7. COSATI CODES 18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) 7. COSATI CODES 18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) 7. COSATI CODES 18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) 7. Low expansion materials . 8 ABSTRACT (Continue on reverse if necessary and identify by block number) . 7. The objective of this effort is to evaluate the stability of low expansion Zerodur, developmental Zerodu 8 ABSTRACT (Continue on reverse if necessary and identify by block number) . 7. The objective of this effort is to evaluate the stability of low expansion Zerodur, developmental Zerodu 8 ABSTRACT (Continue on reverse if necessary and identify by block number) . 7. Low expansion materials is (coating temperatures (300-475K). Zerodum | فالمتعادين والمتكانين المتكانية فستعر الكافات الشاري والكالية | | <u> </u> | | | | | |
| 6. SUPPLEMENTARY NOTATION 7. COSATI CODES 18. SUPCT TERMS (Continue on reverse if necessary and identify by block number) 7. COSATI CODES 18. SUPCT TERMS (Continue on reverse if necessary and identify by block number) 7. COSATI CODES 18. SUPCT TERMS (Continue on reverse if necessary and identify by block number) 7. Continue on reverse if necessary and identify by block number) 7. Low expansion materials . 7. Low expansion to exploit and thetermi | 3a, TYPE OF REPORT 13b, TIM | | 14. DATE OF REP | ORT (Year, Mont | th, Day) 15. PA | AGE COUNT | | |
| 7. COSATI CODES 18. SUJECT TERMS (Continue on reverse if necessary and identify by block number) FIELD GROUP SUB-GROUP 13 Thermal expansion coefficient, Hysteresis, Mirror substrate materials, Thermal properties, Surface figure changes, Low expansion materials Surface figure changes, Low expansion materials 14 Low expansion materials Mistance 15 Stract (continue on reverse if necessary and identify by block number) The objective of this effort is to evaluate the stability of low expansion Zerodur, devel mental Zerodur, ULE, and Cer-Vit as possible substrate materials for high energy laser mirrors. This effort will determine whether there is instability in developmental Zerodu ULE and Cer-Vit over operating temperatures and coating temperatures (300-475K). Zerodur has already been shown to exhibit instability. Thermal cycling will be investigated as a possible approach to eliminate or reduce hysteresis. The effect of polishing on hysteres will also be investigated. 20. DISTRIBUTION / AVAILABILITY OF ABSTRACT DITIC USERS 21 ABSTRACT SECURITY CLASSIFICATION Unclassified as a possible approach to eliminate or reduce hysteresis. The effect of polishing on hysteres will also be investigated. 212. NAME OF RESPONSIBLE INDIVIDUAL DITIC USERS Unclassified Area Code) 220. OFFICE SYMBOL AFWL/ARBD 220. DEFORM 1473, 84 MAR B3 APR edition may be used untilexhausted. SECURITY CLASSIFICATION OF THIS PAGE | | Apr 85 to Jan 87 | 1988, May | | 5 | 2 | | |
| 20 13 materials, Thermal properties, Surface figure changes, Low expansion materials 20 ABSTRACT (Continue on reverse if necessary and identify by block number) The objective of this effort is to evaluate the stability of low expansion Zerodur, devel mental Zerodur, ULE, and Cer-Vit as possible substrate materials for high energy laser mirrors. This effort will determine whether there is instability in developmental Zerodu ULE and Cer-Vit over operating temperatures and coating temperatures (300-475K). Zerodur has already been shown to exhibit instability. Thermal cycling will be investigated as a possible approach to eliminate or reduce hysteresis. The effect of polishing on hysteres will also be investigated. 20. DISTRIBUTION/AVAILABILITY OF ABSTRACT | | | | | | | | |
| PlassTRACT (Continue on reverse if necessary and identify by block number) The objective of this effort is to evaluate the stability of low expansion Zerodur, developmental Zerodur, ULE, and Cer-Vit as possible substrate materials for high energy laser mirrors. This effort will determine whether there is instability in developmental Zerodu ULE and Cer-Vit over operating temperatures and coating temperatures (300-475K). Zerodur has already been shown to exhibit instability. Thermal cycling will be investigated as a possible approach to eliminate or reduce hysteresis. The effect of polishing on hysteres will also be investigated. Provide a control of the set of the | | materials, The | ermal proper | ties. Surf | ace figure | | | |
| 20. DISTRIBUTION / AVAILABILITY OF ABSTRACT 21 ABSTRACT SECURITY CLASSIFICATION 20. DISTRIBUTION / AVAILABILITY OF ABSTRACT 21 ABSTRACT SECURITY CLASSIFICATION 20. DISTRIBUTION / AVAILABILITY OF ABSTRACT 21 ABSTRACT SECURITY CLASSIFICATION 20. DISTRIBUTION / AVAILABILITY OF ABSTRACT 21 ABSTRACT SECURITY CLASSIFICATION 20. DISTRIBUTION / AVAILABILITY OF ABSTRACT 21 ABSTRACT SECURITY CLASSIFICATION 21. ABSTRACT SECURITY CLASSIFICATION 220 OFFICE SYMBOL 22. NAME OF RESPONSIBLE INDIVIDUAL 220 DTELEPHONE (Include Area Code) 22. NAME OF RESPONSIBLE INDIVIDUAL 220 DTELEPHONE (Include Area Code) 22. OFFICE SYMBOL AFWL / ARBD 23 APR edition may be used until exhausted. SECURITY CLASSIFICATION OF THIS PAGE | A LABSTRACT (Continue of structure if | | | (A Lyre | E- | | | |
| mental Zerodur, ULE, and Cer-Vit as possible substrate materials for high energy laser mirrors. This effort will determine whether there is instability in developmental Zerodur ULE and Cer-Vit over operating temperatures and coating temperatures (300-475K). Zerodur has already been shown to exhibit instability. Thermal cycling will be investigated as a possible approach to eliminate or reduce hysteresis. The effect of polishing on hysteres will also be investigated. 20. DISTRIBUTION/AVAILABILITY OF ABSTRACT UNCLASSIFIED/UNLIMITED ABSTRACT SAME AS RPT DIC USERS 21. ABSTRACT SECURITY CLASSIFICATION Unclassified 22a. NAME OF RESPONSIBLE INDIVIDUAL Diane J. Martin 23. APR edition may be used until exhausted. AFWL/ARBD 22c. OFFICE SYMBOL AFWL/ARBD | U ABSTRACT (Continue on reverse if necess | ary and identity by block i | numper) | | | | | |
| UNCLASSIFIED/UNLIMITED Image: Same as RPT DTIC USERS Unclassified 22a. NAME OF RESPONSIBLE INDIVIDUAL 22b. TELEPHONE (Include Area Code) 22c. OFFICE SYMBOL Diane J. Martin (505) 844-1776 AFWL/ARBD DD FORM 1473, 84 MAR 83 APR edition may be used until exhausted. SECURITY CLASSIFICATION OF THIS PAGE | mental Zerodur, ULE, and Cer mirrors. This effort will d ULE and Cer-Vit over operati has already been shown to ex possible approach to elimina | -Vit as possible s etermine whether ng temperatures as hibit instability | substrate ma there is ins nd coating t . Thermal c | terials fo tability i emperature ycling wil | r high ene n developm s (300-475 l be inves | rgy laser ental Zerodur, K). Zerodur tigated as a | | |
| UNCLASSIFIED/UNLIMITED Image: Same as RPT DTIC USERS Unclassified 22a. NAME OF RESPONSIBLE INDIVIDUAL 22b. TELEPHONE (Include Area Code) 22c. OFFICE SYMBOL Diane J. Martin (505) 844-1776 AFWL/ARBD DD FORM 1473, 84 MAR 83 APR edition may be used until exhausted. SECURITY CLASSIFICATION OF THIS PAGE | | | | | | and the second | | |
| UNCLASSIFIED/UNLIMITED Isame as RPT DTIC USERS Unclassified 22a. NAME OF RESPONSIBLE INDIVIDUAL 22b. TELEPHONE (Include Area Code) 22c. OFFICE SYMBOL Diane J. Martin (505) 844-1776 AFWL/ARBD DD FORM 1473, 84 MAR 83 APR edition may be used until exhausted. SECURITY CLASSIFICATION OF THIS PAGE | | | | | | | | |
| UNCLASSIFIED/UNLIMITED Isame as RPT DTIC USERS Unclassified 22a. NAME OF RESPONSIBLE INDIVIDUAL 22b. TELEPHONE (Include Area Code) 22c. OFFICE SYMBOL Diane J. Martin (505) 844-1776 AFWL/ARBD DD FORM 1473, 84 MAR 83 APR edition may be used until exhausted. SECURITY CLASSIFICATION OF THIS PAGE | | | | | | | | |
| UNCLASSIFIED/UNLIMITED Is ame as RPT DTIC USERS Unclassified Iza. NAME OF RESPONSIBLE INDIVIDUAL Is and the set of th | | | | | | <u> </u> | | |
| 22a. NAME OF RESPONSIBLE INDIVIDUAL 22b. TELEPHONE (Include Area Code) 22c. OFFICE SYMBOL Diane J. Martin (505) 844-1776 AFWL/ARBD DD FORM 1473, 84 MAR 83 APR edition may be used until exhausted. SECURITY CLASSIFICATION OF THIS PAGE | | | | | FICATION | ····· | | |
| Diane J. Martin (505) 844-1776 AFWL/ARBD DD FORM 1473, 84 MAR 83 APR edition may be used until exhausted. SECURITY CLASSIFICATION OF THIS PAGE | | AD TIC USERS | 226. TELEPHONE | (Include Area Co | ode) 22c. OFFIC | E SYMBOL | | |
| DD FORM 1473, 84 MAR 83 APR edition may be used until exhausted. SECURITY CLASSIFICATION OF THIS PAGE | | | (505) 844 | -1776 | AFWL/ | ARBD | | |
| | | | ntil avbautto | | | | | |
| | | | | SECURI | TY CLASSIFICATI | ON OF THIS PAGE | | |
| 1 | | | | | | ON OF THIS PAGE | | |

UNCLASSIFIED

Sec. com

í. L

2012

SECURITY CLASSIFICATION OF THIS PAGE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

ACKNOWLEDGEMENTS

We express our appreciation to O. Lindig (Schott), C. Neufeld (Perkin-Elmer), T. Brock (Owens-Illinois), and H. Hagy (Corning) for their assistance in obtaining sample materials.

In addition we thank Prof. R. Shoemaker for administrative guidance; R. Sumner and R. Barreda for optician support; J. Targove and D. Watson for thermal cycling the samples; José Sasian, Steve Johnston, Mathew Watson, and Dan Bass for making the measurements.



| Acces | sion For | |
|-------|----------------------|---|
| NTIS | GRA&I | |
| DTIC | ГАВ | |
| Unann | ounced | |
| Justi | rication_ | |
| | ibution/ lability | |
| | Avail an Specia | • |
| Dist | j Specia. | * |
| A-1 | | |

iii/iv

CONTENTS

Ŷ

| I. | INTRODUCTION 1 |
|------------|--------------------------------------|
| II. | SAMPLE MATERIALS |
| III. | SAMPLE PREPARATION 5 |
| IV. | THERMAL CYCLING |
| V . | DILATOMETER MEASUREMENT METHOD |
| VI. | DILATOMETER RESULTS |
| VII. | SURFACE FIGURE MEASUREMENT METHOD 21 |
| VIII. | SURFACE FIGURE RESULTS |
| IX. | COMPARISON OF DILATOMETER VERSUS |
| | SURFACE FIGURE MEASUREMENTS |
| Х. | CONCLUSIONS |
| XI. | RECOMMENDATIONS |
| XIII. | REFERENCES |

FIGURES

AND AND A PARTY A PURCENCE REPORTED FOR THE PURCH

せいいいいい

| | Pag | ;e |
|-----|--|----|
| 1. | Thermal expansivity versus temperature for Zerodur, ULE, and Cer-Vit | 2 |
| 2. | Dilatometer sample configuration | 4 |
| 3. | Box coater used for nonuniform heating. | 6 |
| 4. | Laser-interferometric dilatometer arrangement | 8 |
| 5. | Detailed study of Zerodur twice cycled 6 K/hr, showing waiting times 1 | 0 |
| 6. | Dilatometer samples cycled 6 K/hr 1 | 1 |
| 7. | Dilatometer samples cycled 60 K/hr 1 | 6 |
| 8. | RTI test arrangement | 2 |
| 9. | Uniform heat - 60 K/hr 2 | 4 |
| 10. | Uniform heat - 6 K/hr 2 | 6 |
| 11. | Nonuniform heating - 90 K/hr 2 | 8 |
| 12. | Uniform heat - 6 K/hr 3 | 1 |
| 13. | Uniform heat - 60 K/hr 3 | 3 |
| 14. | Nonuniform heating - 90 K/hr 3 | 5 |
| 15. | Uniform heat 6 K/hr 3 | 7 |
| 16. | Uniform heat 60 K/hr | 8 |
| 17. | Nonuniform heat 90 K/hr | 9 |

02000

U

I. INTRODUCTION

The objective of this effort is to evaluate the stability of low expansion Zerodur, ULE, and Cer-Vit as possible substrate materials for high energy laser mirrors. This effort will determine whether there is instability in ULE and Cer-Vit over operating and coating temperatures (300 to 475 K). Zerodur has aiready been shown to exhibit instability (Refs. 1 and 2). Thermal cycling will be investigated as a possible approach to eliminate or reduce hysteresis. The effect of polishing on hysteresis will also be investigated.

Background

Figure 1 summarizes the low thermal expansivity properties of Zerodur, ULE, and Cer-Vit. Because of the importance of these materials it is essential that we understand their limitations in order to extend their usefulness and perhaps assist in improving their manufacture.

In 1984, Bennett et al. found that thermal cycling caused permanent deformation in a Zerodur mirror (Ref. 1) when it was heated above 500 K and rapidly cooled in air. Also at that time Jacobs et al. showed (Ref. 2), using laser interferometry, that Zerodur dilatometer samples exhibit hysteresis not only at high temperature (~450 K) but at low temperature (~250 K) upon thermal cycling. In 1985 there was published (Ref. 3) a discussion by the manufacturer of Zerodur in which the cause of Zerodur hysteresis at the higher temperature is attributed to the presence of MgO, deliberately included for its beneficial effect on the viscosity at the melting temperature as well as on obtaining low thermal expansivity. Thus, the presence of MgO aids in achieving uniformity, but at the same time it causes unwanted hysteresis. The article goes on to say that a modified glass ceramic with almost identical properties to those of Zerodur but without the relaxation effects (between 130 and 320° C) has been developed. This experimental Zerodur has been included in the present investigation.

Although inferred in the past, it is of interest to definitely establish the relation between the observed hysteresis and surface deformation. By hysteresis we mean failure to return to former length upon thermal cycling. A simple model suggests that with uniform heating and cooling very little permanent deformation should occur in surface figure, while for non-uniform heating there should be a deformation which does not fully disappear due to the material's failure to fully return to length.

In addition to correlating permanent figure distortion (due to nonuniform heating) with hysteresis (observed with uniform heating) we investigate

- * whether ULE and Cer-Vit exhibit hysteresis effects,
- whether Schott's new experimental (developmental) Zerodur has reduced hysteresis,
- how thermal cycling rate and temperature uniformity affect hysteresis,
- whether (multiple) cycling reduces hysteresis, and
- whether a special polishing procedure developed by the Perkin-Elmer Corporation is effective in reducing Zerodur hysteresis.



Fig. 1. Thermal expansivity versus temperature for Zerodur, ULE, and Cer-Vit.

II. SAMPLE MATERIALS

Samples investigated are listed below.

- 1. Standard Zerodur, manufactured by Schott and polished by AFWL. We call this "Zerodur (AFWL)" or Z_{AFWL}.
- 2. Standard Zerodur, manufactured by Schott and polished at Perkin Corporation by a proprietary method designed to reduce figure distortion upon thermal cycling. We call this "Zerodur (PE)" or Z_{PE}.
- 3. Experimental (developmental) Zerodur, prepared by Schott for reduced hysteresis and reduced distortion upon thermal cycling and polished at Optical Sciences Center. We call this "Developmental Zerodur (OSC)" or Z'_{OSC}.
- Cer-Vit, manufactured by Owens-Illinois Co., obtained through US Naval Weapons Center. We call this "Cer-Vit (OSC)" or C_{OSC}.
- 5. ULE (Corning Type 7971) polished at Optical Sciences Center. We call this "ULE (OSC)" or ULE_{OSC}.

Each material was supplied in two shapes: 8-in.-diam $\times 1$ 1/2-in. discs, to be made into polished mirrors for surface figure studies, and 4-in. long $\times 1$ 1/4-in.-diam cylinders, to be made into etalons for dilatometer studies. Figure 2 shows the etalon configuration.

The first two materials were government furnished equipment, while the remaining material was obtained with the understanding that each supplier would be informed of the experimental results. The original plan was to obtain sufficient material so that figure distortion measurements could be performed with threefold redundancy; e. g., three discs cycled rapidly (60 K/hr) and three discs cycled slowly (6 K/hr). As it turned out, only two Zerodur discs (and four dilatometer samples) were received from Perkin-Elmer, polished by their proprietary method. Schott supplied three discs of experimental Zerodur, as did Corning and Owens-Illinois. The program thus had to proceed with the material available, which meant foregoing the redundancy and going with single samples for each heat treatment.



annaise annais a faisteach

Fig. 2. Dilatometer sample configuration.

0.001

III. SAMPLE PREPARATION

After all rough grinding and boring operations, each dilatometer sample prepared at Optical Sciences Center was stress relieved by immersion in 30 percent hydrogen fluoride acid for 3 min. Care was taken with these samples to avoid thermal shock in the process of optical working (e.g. minimal use of heat in fastening samples during grinding and polishing). Care was also taken not to use scratch marks for identification purposes, as this can introduce strain.

All 8-in -diam discs were polished $\lambda/4$ on both flat surfaces. Prior to surface figure measurements each surface under test was chemically spray silvered to improve measurement contrast. To preserve the excellent surface finish from chemical degradation, the thin (~5 nm) silver coating was removed before thermal cycling and then reapplied before surface remeasurement.

Spray silvering is a simple process to increase the reflectivity of a glass substrate. The main advantages over an evaporation process are that it can be done in a comparatively short period of time, no heat or ion bombardment treatments are required, and the cost is low. The important requirement to meet by a spray coated film is that the nonuniformities of the film thickness must be smaller than the thickness noise level of the measurement system. Reproducibility of data for different films on the same substrate justify the choice of spray silvering as the coating process preferred for this study.

IV. THERMAL CYCLING

Uniform Heating

The 8-in discs were temperature cycled, supported on edge, in an oven at the Mirror Laboratory. The two cycling runs were controlled to increase temperature from room temperature and to decrease temperature at 6 and 60 K/hr, respectively with 1 hour holds at the maximum temperature (475 K).

Nonuniform Heating

Nonuniform heating was done simulating the conditions of a standard coating cycle except that no coating was applied. The 8-in. discs were mounted, three at a time, in a Balzers BAK 760 Box Coater. Radiant heat was incident from the backside of each sample as it rotated past the heat source. Figure 3 shows the mounting geometry.

Temperature was cycled from room temperature to 475 K in 2 hours. Then it was held for several hours before cooling back to room temperature in 2 hours.



Fig. 3. Box coater used for nonuniform heating.

V. DILATOMETER MEASUREMENT METHOD

Samples were fashioned into hollow cylinders with parallel ends and a hole down the symmetry axis. Polished, highly reflecting end-mirrors were attached, optically contacted to each end, forming a Fabry-Perot resonator. The sample/etalon was then mounted in an evacuated copper chamber and a tunable HeNe laser beam was frequency-locked to a cavity resonance. As shown schematically in Figure 4, part of the tunable laser beam was split off to compare (beat) it with a stabilized reference laser beam to monitor changes in cavity resonant frequency. As the sample length L changed by an amount ΔL , the cavity resonant frequency ν changed by an amount $\Delta \nu = (\nu/L)\Delta L$ which was sensed electrically as a change in the beat frequency. Thus a tiny length change causes a large change in beat frequency, which can be measured conveniently.

The limiting measurement error in $\Delta L/L$ is set for samples of low expansivity by the stability of the reference laser which is better than 10^{-9} . For samples whose thermal expansivity is not low, the accuracy is limited by temperature measurement and control: $\Delta L/L = \alpha \Delta T$. In our apparatus the error in ΔT is about 0.01 K.

The general procedure was to thermally cycle, in 25 K steps, from room temperature up to 475 K and back to room temperature. The temperature rate of change was computercontrolled by an Hewlett Packard 85 computer and Lakeshore DRC 81 C temperature controller. To reach thermal equilibrium the system's normal time constant was about 3 hours. However, for Zerodur, long waiting times are associated with the hysteresis phenomenon. To show this, we made a detailed study of one sample in which we recorded these waiting times. We also repeated the cycling to determine whether repeated cycling can reduce the hysteresis.



Fig. 4. Laser-interferometric dilatometer arrangement.

VI. DILATOMETER RESULTS

Repeated cycling of standard Zerodur

As the data for "Zerodur 6 K/hr" showed unusually poor reproducibility after one thermal cycling, this sample was selected for detailed study to investigate what is and is not improved by repeated thermal cycling. Referring to Figure 5, the numbers indicate what Schott calls the waiting time, in hours, for each 25 K equilibrium increment. A number of features are noteworthy.

The first temperature rise traces a path which is never again repeated. Subsequent cycling results in a fairly repeatable path which includes hysteresis. Interpretation of the altered preliminary behavior is that this particular sample had some strain, probably from thermal shock during optical working, whose effects were removed by thermal cycling. We believe this because measurements of another sample, "Zerodur 60 K/hr", showed much better reproducibility, despite its faster cycling which would be expected to cause worse hysteresis. Note that waiting times were unusually long for a nonhysteresis temperature region. This behavior may be associated with annealing out of strain.

Slow versus fast cycling

- A. Zerodur (AFWL), 6 and 60 K/hr (Figs. 6a and 7a). The slower cycling was discussed previously. Note that the faster cycled sample has better reproducibility (less strain) but worse hysteresis. ("Sawtooth" peak-to-valley depth is larger).
- B. Zerodur (PE), 6 and 60 K/hr (Figs. 6b and 7b). Both show presence of hysteresis. Hysteresis is more pronounced in the faster cycled case. In both cases there is about 1 ppm of displacement (released strain) on the return to room temperature.
- C. Developmental Zerodur, 6 and 60 K/hr (Figs. 6c and 7c). Only the slightest trace of hysteresis.
- D. ULE, 6 and 60 K/hr (Figs. 6d and 7d). No trace of hysteresis.
- E. Cer-Vit, 6 and 60 K/hr (Figs. 6e and 7e). No trace of hysteresis.



Fig. 5. Detailed study of Zerodur twice cycled 6 K/hr, showing waiting times.



Fig. 6a. Dilatometer sample of Zerodur cycled 6 K/hr.



DEVELOPMENTAL ZERODUR (OSC) CYCLED 6 K/HR





Fig. 6c. Continued.







Fig. 7a. Dilatometer sample of Zerodur cycled 60 K/hr.







ТЕМР (К) 250 300 350 400 450

Fig. 7c. Continued.



Fig. 7d. Continued.



VII. SURFACE FIGURE MEASUREMENT METHOD

To characterize the surfaces, a real time Twyman-Green phase shifting interferometer was mounted on an air-suspended 8000 lb granite table. An entire underground room was dedicated to conducting these measurements. At early stages it became clear that to achieve data reproducibility, the measurement system has to be isolated. The effects of the system disturbing factors could be readily observed on the real time interference pattern. These effects of the system disturbing factors could be readily observed on the real time interference (RTI) pattern. These effects were vibrations of the fringe pattern, fringe drifting, and fringe distortion. They were mainly caused by building vibrations and sound, system temperature changes, and air turbulence.

To overcome these disturbing effects the massive granite table supporting the test setup had to be air suspended. The masses of the interferometer and mirror mounts were augmented to decrease their natural resonance frequency. To minimize thermal effects, a thermal insulation Styrofoam enclosure was constructed to cover the entire test setup, which also improved air stability of the optical testing path. The test instruments were left on throughout all the test period, the testing room conditions were kept the same, and testing was always conducted at the same time of day. As a result of these precautions a notable improvement in fringe stability was obtained which led to data reproducibility with the required precision.

A reference mirror was incorporated to monitor the system performance and verify that for each measurement the test configuration remained the same (Fig. 8). As discussed in Section III, prior to each RTI measurement each surface was coated chemically with a thin film of silver to increase its reflectivity; the coating was later removed before thermal cycling. The effective aperture diameter was about 7 in. because edge diffraction effects introduced spurious data which led us to ignore the outermost rim.

Thirty data sets were taken for each sample before and after heat treatment. Averages were then computed and the differences of those averages were obtained to determine the change in optical figure. Referring to Figures 9 through 11, this change is presented as a surface contour for each sample in the left-hand column; the number given represents the root-mean-square (RMS) surface change (in visible wavelengths). Immediately following each sample measurement the same procedure was followed for the reference (sample removed). The change in reference figure is presented in the right-hand column of the Figures 9 through 11, along with RMS changes. The data processing was accomplished with WISP software from WYKO Corporation, Tucson, Arizona.

Each data set provides a surface contour obtained through phase-shifting interferometry. The set of figures that show the change in reference surface provide information about the system reproducibility as well as the system precision. These system characteristics are within the specifications required: $(\lambda/50)$.

Surface contours are preferred for displaying global results, rather than simple numerical quantities which often fail to adequately describe information for this study of surface distortion. An estimate of the reliability of each measured change in sample figure may be obtained by forming a signal-to-noise ratio using the RMS change in sample figure as signal, and the RMS change in reference as noise.



Fig. 8. RTI test arrangement.

VIII. SURFACE FIGURE RESULTS

1. Uniform heating - 60 K/hr (Figs. 9a and 9b).

The 8-in. discs of five materials were thermally cycled 300 to 475 K at 60 K/hr to determine figure changes. The left- and right-hand columns respectively show sample changes before versus after heating and changes in the reference (system reproducibility). Our general conclusion is that 60 K/hr uniform heating caused no significant change in surface figure.

2. Uniform heating - 6 K/hr (Figs. 10a and 10b).

We expected to see even less distortion at 6 K/hr than at 60 K/hr; this indeed was what we saw, except for the case of ULE, which showed quite a significant distortion. Because of the excellent ULE fast-cycling behavior, as well as previous experience with ULE (ours and Bennett's) we believe that this sample probably had unusual strain in it. The conclusion is that, despite the ULE result, 6 K/hr uniform heating generally caused no significant change in surface figure.

3. Nonuniform heating - 90 K/hr (Figs. 11a and 11b).

Figure 3 shows the configuration of the vacuum coater used for nonuniform heating. The coater accommodated three 8-in. samples. Therefore, to maintain good mechanical balance, we added a second developmental Zerodur sample to the five. This resulted in two thermal cycling runs of three samples each.

The results are very striking. Both the Air Force Weapons Lab- and Perkin-Elmerpolished Zerodur showed significant distortion, while none of the others did. Especially noteworthy are the two samples of developmental Zerodur, Z'_{OSC} , which showed no significant distortion. (One was distorted a little more than the other, but far less than standard Zerodur).







 $\Delta Z'_{osc}$





UNIFORM HEAT CYCLED 300-475K 6 K/hr

•





Fig. 9b. Concluded.

UNIFORM HEAT CYCLED 300-475K 60K/hr



Fig. 10a. Uniform heat - 6 K/hr.

UNIFORM HEAT CYCLED 300-475K 60K/hr



Fig. 10b. Concluded.

.006 λ





NONUNIFORM HEAT CYCLED 300-475 K 90 K/hr



Fig. 11b. Concluded.
IX. COMPARISON OF DILATOMETER VERSUS SURFACE FIGURE MEASUREMENTS

Overview

In Figures 15 through 17 the dilatometer versus surface figure measurements were compared directly. To emphasize the correlation between hysteresis and figure distortion, we have deleted from the dilatometer curves many identification details, which were presented in Section VI.

In Figure 14, nonuniform heat, 90 K/hr, the dilatometer curves are the same as those for 60 K/hr. Thus the comparison is only approximate when it comes to cycling rate.

Details

Figures 9 through 11 and 12 through 14 present the same data as is shown in the overview, but without deletion of details, and grouped for direct comparison of surface data versus dilatometer curves.



(

1

Fig. 12a. Uniform heat - 6 K/hr.

1 1 1



Fig. 12b. Concluded.



Fig. 13a. Uniform heat - 60 K/hr.



Fig. 13b. Concluded.



Constant of the second s

O Contraction

€ E

Fig. 14a. Nonuniform heating - 90 K/hr.



•

Fig. 14b. Concluded.



UNIFORM HEAT Cycled 300-475k 60k/hr







Fig. 17. Nonuniform heat 90 K/hr.

X. CONCLUSIONS

This investigation has been successful in answering many questions about the best low expansion mirror materials presently available. It has demonstrated quantitatively the relation between hysteresis and figure distortion, and has extended the earlier findings of Bennett et al. In addition, the present results should prove useful as guidelines in the manufacture of improved dimensionally stable materials.

We summarize below the findings of this work:

•

- 1. Cer-Vit and ULE exhibit no significant hysteresis figure distortion under the conditions of this study, even though the Cer-Vit showed obvious strain birefringence with crossed-polaroid examination.
- 2. In Standard Zerodur the hysteresis present appears to be responsible for surface figure distortion (about $\lambda/10$ across 8 in.). Additional strain (several ppm) is sometimes present which can be annealed out by thermal cycling. This strain may be due to thermal shock or machining procedures.
- 3. Uniform heating (300 to 475 K) causes no significant surface deformation in any of the materials studied here; however, nonuniform heating does cause surface deformation in materials which have hysteresis. This agrees with a simple model of thermal relaxation. Bennett et al. found that standard Zerodur became distorted when uniformly heated to 250°C (523 K) and 300°C (573 K) and then quenched (rapidly air-cooled). The present results add to this the fact that distortion can take place at even lower temperatures (~450 K, where hysteresis sets in), but is due to nonuniformity of heating. This suggests that in the Bennett study the culprit was the quenching, which introduced nonuniformity into the cooling process. Our study agrees with and complements Bennett's finding that ULE exhibits no distortion.
- 4. Concerning effect of *rate* of cycling on hysteresis produced, we show that 60 K/hr generally causes more severe hysteresis than 6 K/hr in standard Zerodur.
- 5. The Perkin-Elmer treatment produced no significant reduction in standard Zerodur surface distortion, compared with standard Zerodur prepared by AFWL polishing procedures. The only difference observed was that the PE treated material was free from first-run irreversible characteristics. The PE treated material still had standard Zerodur hysteresis, but behaved as if it had already received some thermal cycling to relieve strains. In the present work we have demonstrated that thermal cycling can eliminate failure to return to length due to strain, but apparently it cannot eliminate hysteresis caused by structural components such as MgO.

6. Schott's new developmental material was virtually free of hysteresis and surface figure distortion under the conditions of these tests. This result indicates a connection between hysteresis and figure distortion. (No hysteresis; no figure distortion) Schott apparently anticipated this and removed the hysteresis-causing MgO from the recipe of the new material. Schott is to be congratulated on whileving this without sacrificing low expansion characteristics.

XI. RECOMMENDATIONS

Uniformity of thermal expansion is every bit as important as low thermal expansion in the performance of a telescope mirror. For this reason, the good news about Schott's experimental material must be followed up with evaluation of its thermal expansion uniformity.

We recommend that Schott make available samples from a large ingot of the new material, selected in such a way that the variation of CTE can be mapped and CTE gradient obtained in much the same way as was done for Heraeus TO8E fused quartz.⁴

Other characteristics which should be evaluated for the new material include its CTE at low temperatures and whether there is still hysteresis at low temperatures (~ 250 K) as Lindig et al. (Ref. 3) predicted there might be.

Two 8-in. polished flats of each material have been returned to AFWL for further testing.

XII. REFERENCES

- 1. H. H. Shaffer and H. Bennett, "Effect of thermal cycling on dimensional stability of Zerodur and ULE," Appl Opt. 23, 2852 (1984).
- 2. S. F. Jacobs, S. C. Johnston, and G. A. Hansen, "Expansion hysteresis upon thermal cycling of Zerodur," Appl. Opt. 23, 3014 (1984).
- 3. O. Lindig and W. Pannhorst, "Thermal expansion and length stability of Zerodur in dependence on temperature and time," Appl. Opt. 24 3330 (1985).
- 4. S. F. Jacobs, D. Shough, and C. Connors, "Thermal expansion uniformity of materials for large telescope mirrors," Appl. Opt. 6(23), 4237 (1984).