LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
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Specification **LIGO-E960123-02 - E** 8/1/97

Beam Tube Bakeout
Design Requirements Document

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Distribution of this draft:

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Abstract

This document specifies the design requirements for the Beam Tube Bakeout to be used at the LIGO sites. It covers the heating power and control, thermal insulation, pumping and instrumentation, data acquisition, and electrical requirements to execute the beam tube bake.

1 INTRODUCTION

1.1. Purpose

The purpose of this document is to define the requirements for the bakeout of the LIGO Beam Tube Modules. These requirements will be used to guide the design and testing of bakeout equipment and procedures.

1.2. Scope

This document provides requirements for the bakeout equipment (heating power and controls, thermal insulation, pumping, instrumentation, data acquisition and logging), processes (equipment setup and conduct of the bakeout, and post-bakeout data analysis) and electrical requirements to be used for the beam tube bakeout.

1.3. Definitions

1.4. Acronyms

AC	Alternating Current
AMU	Atomic Mass Unit
BT	Beam Tube
BTD	Beam Tube Demonstration
BTE	Beam Tube Enclosure
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DAS	Data Acquisition System
DC	Direct Current
DRD	Design Requirements Document
LIGO	Laser Interferometer Gravitational Wave Observatory
LN_2	Liquid Nitrogen
PLC	Programmable Logic Controller
QT	Qualification Test
RGA	Residual Gas Analyzer
TBS	To Be Supplied

1.5. Applicable Documents

1.5.1. LIGO Documents

M950001	Project Management Plan, latest revision
E950018	Science Requirements Document, latest revision
E950020	Beam Tube Module Requirements-Fabrication & Installation Contract, latest revision
E940002	Vacuum Equipment Specification, latest revision
E94xxxx	Beam Tube Module Specification (formerly Specification No. 1100004)
E94xxxx	Process Specification for Low Hydrogen, Type 304L Stainless Steel Vacuum Products (formerly Specification No. 1100007)
M96xxxx	Configuration Management Plan, latest revision
M950046	Project System Safety Plan, latest revision
D950027	Beam Tube Pump Port Hardware, latest revision
E950089	Interface Control Document (ICD): Beam Tube (BT) - Civil Construction (CC), latest revision

1.5.2. Non-LIGO Documents

2 GENERAL DESCRIPTION

2.1. Product Perspective

The LIGO Beam Tube Modules will be fabricated and installed by a contractor, CBI, Inc. Current plans call for conducting a bakeout (the subject of this document) of each beam tube module before integration with the rest of the LIGO vacuum system.

2.2. Product Functions

The beam tube modules will be unbaked when accepted from the contractor. At that point, partial pressures for H_2O and hydrocarbon gas species will exceed LIGO partial pressure goals. The beam tube bakeout is intended to reduce these partial pressures to the goal levels.

2.3. General Constraints

The beam tube is already designed and is under construction. The bakeout must meet its objectives without modification to the beam tube design, and must not subject the beam tube, attached components (such as gate valves), foundations or enclosure to stresses beyond the capabilities of the existing design.

Some beam tube bakeout requirements are derived from empirical results obtained during earlier test programs.

To reduce significant capital costs, the equipment required for the bakeout will be used sequentially on each 2 km beam tube module, first at the Hanford, Washington site and then at the Livingston, Louisiana site.

2.4. Assumptions and Dependencies

The following factors affect the scope of the bakeout task and, if these change, then the scope may have to be changed accordingly:

- The beam tube will be baked out in increments of 2 kilometer modules.
- Adequate AC power (13.8 kV, 1300 kVA) will be available along the beam tubes.
- Safe access to beam tube enclosures during installation and bake (if needed) will be allowed.
- The beam tube will have been accepted from the beam tube fabrication and installation contractor and will meet its performance requirements (E950020).
- The beam tube is left under rough vacuum up to the time of the bakeout.
- Leaks larger than the LIGO specification which are present after the bakeout will be identified and localized, but repair/recovery procedures are not within the scope of this document.
- Insulation and thermal sensors may be left in place after each beam tube module is baked.

3 REQUIREMENTS

The allowable residual gas pressure in the beam tubes is set by the anticipated sensitivity of the detectors in the LIGO. The LIGO Science Requirements Document (referenced in 1.5.1 above) sets the goal for residual gas pressure “...at a level at or below an equivalent strain noise of 2×10^{-25} Hz^{-}”. The beam tube bakeout is intended to reduce the rate of outgassing of adsorbed gases (principally H_2O, but also CO, CO_2, CH_4 and heavier hydrocarbons) to a level which meets the residual gas pressure goal when the beam tube modules are pumped from their ends only (2 km points).

The bakeout requirements are derived from the above primary consideration and the empirical results achieved during the successful Qualification Test (QT) and earlier Beam Tube Demonstration (BTD) bakeouts.

3.1. Characteristics

3.1.1. Performance Characteristics

3.1.1.1 Components to be Baked

All vacuum surfaces of the bake volume, including beam tube wall material, expansion joints, pump ports, pump port hardware, 114/122 cm gate valves, and terminations shall be maintained within temperature limits specified below during the module bake.

3.1.1.2 Partial Pressures During the Bakeout

Partial pressures during the bake shall be controlled (by suitable choice of pumping speeds and control of temperature rate-of-rise) to maintain attached RGA(s) in their linear range to ensure proper operation throughout the bake.

Partial pressures of condensable gases shall be sufficiently low at the end of the bakeout and during cool down to avoid re-adsorption. The partial pressure for water vapor at an average bake temperature of 150˚C at the end of the bakeout interval shall be $P(H_2O) < 2\times10^{-8}$ torr, and the sum of partial pressures for AMUs 41, 43, 55 and 57 shall be $P(41,43,55,57) < 2\times10^{-9}$ torr.

3.1.1.3 Bake Temperature

3.1.1.3.1 Minimum Temperature

The temperature of any point along the surface of beam tube bakeout volume shall be greater than 130˚C.

3.1.1.3.2 Maximum Temperature of Beam Tube Wall

In order to avoid mechanical overstress of the beam tube wall structure, the maximum temperature at any point on the spiral welded beam tube wall shall be less than TBD (170˚C).

3.1.1.3.3 Maximum Temperature of Beam Tube Bellows

The temperature at any point on any beam tube bellows shall be less than TBD˚C (presently assumed to be quite high -- looking for the limiting driver).

3.1.1.3.4 Maximum Difference in Temperatures of the Beam Tube Wall

In order to avoid mechanical overstress (axial) of the beam tube support structures, the average temperature of any individual 20 m-long section of the beam tube wall shall not differ from the average temperature of any other section by more than 40˚C (ref: Appendix A).

In order to avoid mechanical overstress (transverse, horizontal) of the beam tube support structures due to thermally-induced “banana mode” distortions, the average temperature of any semicylindrical left half of any individual 20 m-long section shall not differ from the average temperature of its corresponding semicylindrical right half by more than 5˚C (ref: Appendix B).

In order to avoid mechanical overstress (vertical) of the beam tube support structures due to thermally-induced “banana mode” distortions, the average temperature of any semicylindrical upper half of any individual 20 m-long section shall not differ from the average temperature of its corresponding semicylindrical lower half by more than 30˚C (ref: Appendix B).

3.1.1.3.5 Maximum Temperature of 114/122 cm Gate Valves

In order to avoid over heating of the 114/122 cm gate valve O-rings, the maximum temperature at any point on the gate or gate valve body shall not exceed 170˚C. Valve motor and electronics shall be removed during the bakeout.

3.1.1.3.6 Maximum Temperature of Other (TBD) Components

TBD.

3.1.1.4 Beam Tube Insulation

Beam tube walls shall be insulated as required to achieve the above temperature limits.

3.1.1.5 Bake Duration

The coldest spot of the beam tube module under bakeout shall be maintained above the minimum temperature (3.1.1.3.1) for the earlier of either an elapsed time of 30 days, or until the water (H_2O) outgassing rate has decreased to $J(H_2O) < 1\times10^{-11}$ torr l/s cm^2 at 150˚C. If the temperature of any sensor monitoring the vacuum wall surfaces falls below the minimum bake temperature, the bake time shall be extended as needed to ensure that the minimum time requirement is met.

3.1.1.6 Data Acquisition, Display, Monitoring and Recording

The beam tube module shall be instrumented to measure the wall temperatures at representative positions, including anticipated hot or cold spots, interfaces with pump port hardware, 114/122 cm gate valves and terminations. The beam tube module shall also be instrumented with at least one RGA to measure partial pressures through AMU 100 during the bakeout (10^{-9} torr instrument sensitivity), and partial pressures through AMU 100 during post-bake (10^{-15} torr sensitivity) measurements. Instrumentation shall also be provided to measure DC power supply currents and voltages, operating status of equipment (such as vacuum pumps), and such other engineering data, including ambient environmental conditions (temperature, humidity, wind speed and direction), which determine the state of bakeout equipment.

During the initial bakeout, the equipment shall include provisions for measuring representative strains on the beam tube structure. During post-bake measurements, the equipment shall include provisions for measuring pumping speeds and outgassing rates.

All needed data shall be available at a single location for the purposes of display, monitoring and recording.

All acquired data shall be time stamped and recorded as needed (at approximately 15 minute intervals during bake) and the accumulated data file shall be archived periodically.

3.1.1.7 Vacuum Components

All vacuum components attached to the beam tube module shall comply with the requirements given in the LIGO Vacuum Equipment Specification, section 5, for similar components.

3.1.2. Physical Characteristics

The bakeout equipment, excluding beam tube insulation and temperature sensors, shall be installed and de-installed from module to module during the bake of subsequent modules. In addition, this equipment shall be transportable from site to site.

3.1.3. Interface Definitions

3.1.3.1 Interfaces to other LIGO systems

3.1.3.1.1 Mechanical Interfaces

The vacuum hardware shall be compatible with the BT module pump ports hardware, Type H, as called out in drawing D950027.

Electrical connections for delivering DC heating power to the beam tube module shall use clamp-on attachments to beam tube support rings at nearby pump ports.

Temperature sensors shall be attached to the beam tube wall using TBD technique.

3.1.3.1.2 Electrical Interfaces

Step-down transformers shall be used to provide needed AC power (480VAC, 208 VAC, 120VAC) from the site power (13.8 kV, WA; 13.2 kV, LA). Up to 1300 kVA is required.

The beam tube module shall be grounded at the ends and midpoint only during the bake.

The beam tube modules shall have electrical connections to DC power supplies for heating.

Monitoring and recording devices shall use AC power (110-120VAC), also derived from site utilities power.

The bakeout equipment shall have adequate protection from lightning.

3.1.3.1.3 Optical Interfaces

There are no optical interfaces.

3.1.3.1.4 Thermal Interfaces

No special provisions other than insulation and heating of the beam tube walls will be made to influence the thermal behavior of the beam tube or Beam Tube Enclosure during the bakeout.

3.1.3.1.5 Stay Clear Zones

Access to beam tube enclosure shall be restricted during bake. Access to all service and emergency entrances to module under bake shall be kept clear during the duration of the bake activities.

3.1.4. Reliability/Maintainability

As a minimum, system design shall be such to provide a 30 day bake period with 90% confidence that the bakeout performance requirements are met (reference 3.1.1).

The insulation blanket shall have a minimum usable lifetime of 1 bake cycle. As a goal, a 10 year lifetime is desired.

The thermal sensors shall have a minimum usable life of 20 years installed.

The insulation blanket shall be constructed of materials which do not pose a threat of long-term corrosion of the stainless steel tube wall or reinforcing rings.

3.1.5. Environmental Conditions

The beam tube bakeout equipment shall be able to achieve and maintain design bake temperatures under anticipated temperature extremes at either site. The equipment must be safe to other equipment and personnel during exceptional circumstances such as a power failure, earthquake, lightning, etc.

3.1.5.1 Natural Environment

3.1.5.1.1 Temperature and Humidity

Table 1: Environmental Performance Characteristics

	Operating	***Non-operating (storage)***	***Transport***
Equipment in contact with beam tube wall	0˚C to +200˚C, 0-90%RH	-40˚C to +70˚C, 0-100% RH	-40˚C to +70˚C, 0-90% RH
Equipment located inside the BTE	0˚C to +70˚C, 0-90%RH	-40˚C to +70˚C, 0-100% RH	-40˚C to +70˚C, 0-90% RH
Equipment located outside the BTE	-30˚C to +40˚C, 0-100%RH	-40˚C to +70˚C, 0-100% RH	-40˚C to +70˚C, 0-90% RH
Equipment located inside buildings	20˚C to 30˚C, 20-70%RH	-40˚C to +70˚C, 0-100% RH	-40˚C to +70˚C, 0-90% RH

3.1.5.1.2 Atmospheric Pressure

TBD

3.1.5.1.3 Seismic Disturbance

TBD

3.1.5.2 Induced Environment

3.1.5.2.1 Electromagnetic Radiation

TBD

3.1.5.2.2 Acoustic

TBD

3.1.5.2.3 Mechanical Vibration

TBD

3.1.6. Transportability

All removable bakeout equipment shall be packaged to be transported between beam tube modules with minimum labor required for transportation and setup. All equipment shall be transportable across the country by commercial carrier without degradation in performance. If necessary, provisions shall be made for measuring and controlling environmental conditions (temperature and accelerations) during transport and handling. Special shipping containers, shipping and handling mechanical restraints, and shock isolation shall be utilized to prevent damage. All containers shall be movable by forklift. All items over 100 lbs. which must be moved into place within LIGO buildings shall have appropriate lifting eyes and mechanical strength to be lifted by cranes.

3.2. Design and Construction

3.2.1. Materials and Processes

3.2.1.1 Finishes

The beam tube insulation shall include an integral exterior vapor barrier, and shall be installed in a manner which ensures a seal against atmospheric moisture penetration.

3.2.1.2 Materials

Surface-to-surface contact between dissimilar metals shall be controlled in accordance with the best available practices for corrosion prevention and control.

Insulation shall be constructed of materials which do not introduce a life safety hazard, and do not pose a threat to long-term corrosion of the stainless steel tube wall or reinforcing rings.

Insulation shall not emit toxic gasses when the beam tube is heated to bake temperature.

3.2.1.3 Processes

All processes critical to the success of the bakeout activity shall be specified and controlled by the detailed design documentation.

3.2.2. Component Naming

Component names shall be designated in the detailed design documentation.

3.2.3. Workmanship

Insulation shall be installed in a workmanlike manner by skilled workmen regularly engaged in this type of work. All materials shall be installed in accordance with the manufacturer's recommendations, applicable building codes and industrial standards.

3.2.4. Interchangeability

N/A

3.2.5. Safety

Equipment and procedures associated with executing bakeout task shall meet all applicable Federal safety regulations, plus applicable State, Local and LIGO safety requirements. A hazard/risk analysis shall be conducted in accordance with guidelines set forth in the LIGO Project System Safety Plan. Special issues expected to be addressed includes:

- working in confined space (controlled access to beam tube enclosure)
- high power (up to 1.3 MW)
- high current (2000 A)
- high voltage (13.8 kV)
- high temperature (150˚C)
- lightning protection

3.3. Documentation

3.3.1. Specifications

T970xxx	Specification for Beam Tube Insulation

3.3.2. Design Documents

T960124	Issues and Consideration on the Beam Tube Bake, Nov. 30, 1995.
T96xxxx	Information for the Bakeout Design, Aug. 12, 1996.
T960178	Beam Tube Bakeout Conceptual Design
T970148	Beam Tube Bakeout Preliminary Design

3.3.3. Engineering Drawings and Associated Lists

3.3.4. Technical Manuals and Procedures

Procedures shall be provided for, at minimum,

- Initial installation and setup of equipment
- Normal operation of equipment
- Normal and emergency shut down
- Normal and/or preventive maintenance

- Troubleshooting guide for anticipated potential malfunctions

3.3.5. Documentation Numbering

All documents shall be numbered and identified in accordance with the LIGO documentation numbering system LIGO document TBD

3.3.6. Test Plans and Procedures

All test plans and procedures shall be developed in accordance with applicable LIGO Test Plan Guidelines, LIGO document TBD.

3.4. Logistics

The design shall include a list of all recommended spare parts and special test equipment required.

4 QUALITY ASSURANCE PROVISIONS

4.1. General

4.1.1. Responsibility for Tests

Responsibility for bakeout testing and execution lies with the Observatory Head at each LIGO site. Tests shall be carried out by on-site personnel specially trained for and dedicated to the beam tube bakeout task.

4.1.2. Special Tests

4.1.2.1 Engineering Tests

Engineering tests to evaluate the response of the beam tube structure to stresses from the bakeout shall be incorporated and integrated into the testing of the first beam tube module to be baked out.

4.1.2.2 Reliability Testing

Reliability evaluation/development tests shall be conducted as deemed necessary on the first beam tube module to be baked out.

4.1.3. Configuration Management

Configuration control of specifications and designs shall be in accordance with the LIGO Configuration Management Plan.

4.2. Quality conformance inspections

Design and performance requirements identified in this specification and referenced specifications shall be verified by analysis, demonstration, or test. Verification method selection shall be specified by individual specifications, and documented by appropriate test and evaluation plans and procedures. Verification of compliance to the requirements of this and subsequent specifications may be accomplished by the following methods or combination of methods:

4.2.1. Inspections

TBD

4.2.2. Analysis

TBD

4.2.3. Demonstration

TBD

4.2.4. Test

TBD

APPENDIX A DETERMINATION OF MAXIMUM ALLOWABLE AXIAL THERMAL GRADIENTS.

A model was developed to determine the maximum allowable axial thermal gradients during bake out. The components of the model were:

[1] Maximum allowable force on BT fixed supports. This includes both seismic (F < 2169 lb) and thermal (F < 5188 lb) allowances; total maximum allowable force is thus F < 7357 lb. The values are from the Beam Tube (BT)-Civil Construction (CC) Interface Control Document (ICD) and correspond to design values provided by CB&I and Parsons for the BT design and associated slab interfaces.

[2] Thermal expansion characteristics for the BT material (304L SS).

[3] The distribution function of expansion joint spring constants. The statistical representation was derived from CB&I empirical data for the first 42 joints, which have mean and standard deviations of 4677 lb/in and 140 lb/in, respectively (Figure A-1). Note that these spring constants have been corrected for the Hyspan calibration error in reporting the original data. The model incorporated the 42 data points and random samples of the distribution for the remaining expansion joints.

[4] Axial loads at the module ends caused by atmospheric pressure on the evacuated beam tube.

Using these parameters as inputs, the model was used to generate representative chains of 50 x 40 m long tube sections (length between fixed supports). A temperature difference dT was imposed on alternating segments consisting of lengths between fixed supports. The distribution of resulting axial forces at the fixed supports was determined and maximum thermal gradient was determined which could satisfy the maximum load limits from [1] above (Figures A-2). As seen in the figure, for bellows distributed like the first 42 delivered, forces are safely within the maximum allowable limits when dT = 40°C.

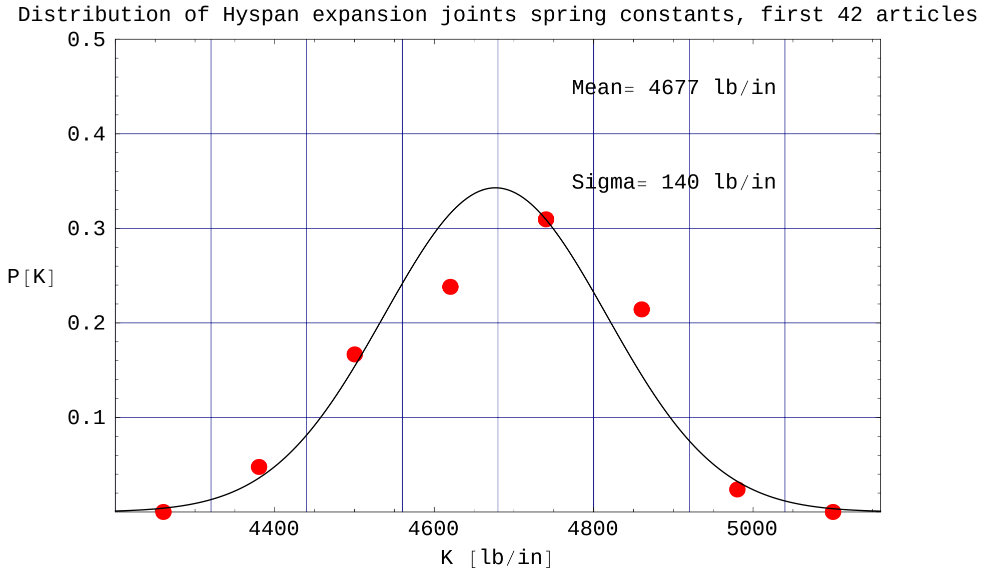

Figure A-1: Distribution of Hyspan expansion joints spring constants, first 42 articles

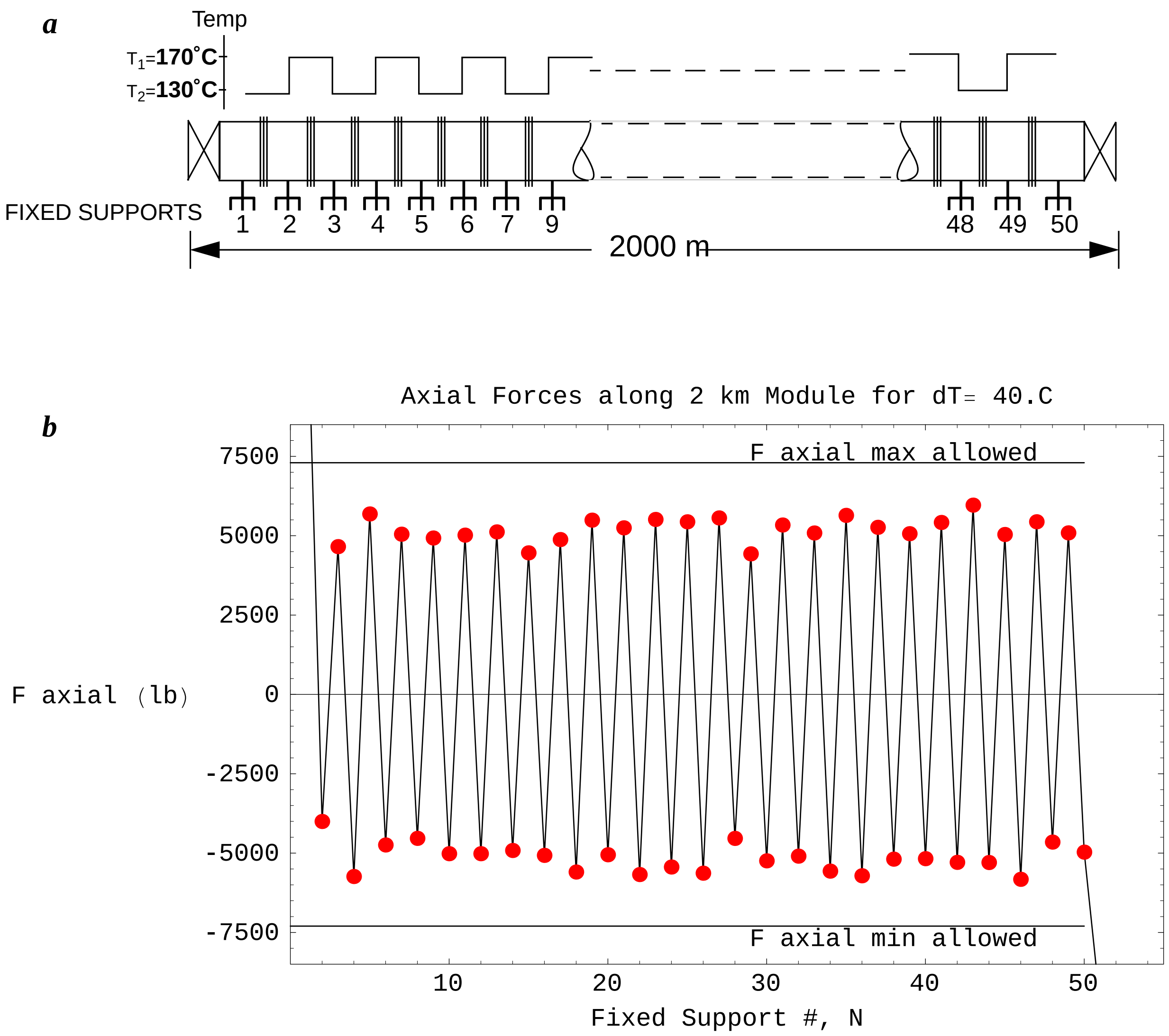

Figure A-2: (*a*) Temperature distribution used to calculate axial forces; (*b*) Axial forces at fixed supports with tube sections between adjacent pairs of supports at alternating temperatures (for temperature difference dT=40°C)

APPENDIX B DETERMINATION OF MAXIMUM ALLOWABLE TRANSVERSE (HORIZONTAL AND VERTICAL) THERMAL GRADIENTS.

A model has been developed to determine the maximum allowable transverse thermal gradients during bake out. If a free section of beam tube experiences a difference in temperature between two opposing halves of the cylinder, it will assume a banana shape (dotted shape in Figure B-1). The model was used to calculate the force required to restore a free beam tube section thus distorted back into a linear shape, a constraint imposed by the beam tube supports. The supports must exert the required force in the presence of such a thermal gradient across the beam tube.

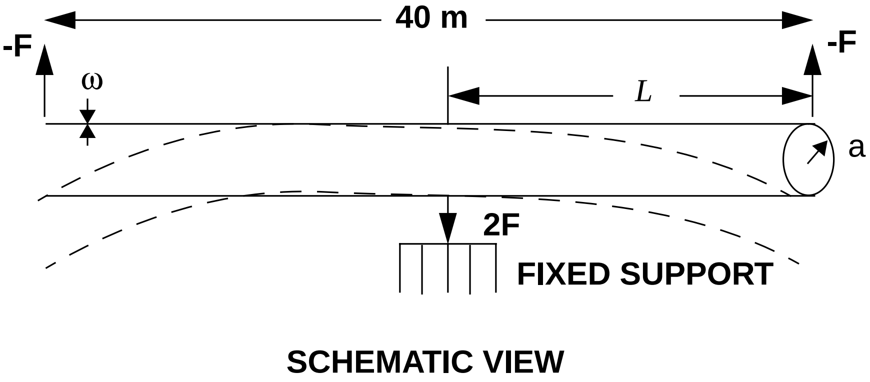

Figure B-1: Illustration of model parameters used to determine allowable transverse forces: *elevation view* for vertical forces; *plan view* for horizontal forces.

The force *F* exerted by a guided support (the fixed support exerts a force 2*F)* is given by*:*

$$F(\Delta T) = \frac{3\pi Y a^3 \omega\alpha}{2L} \cdot \frac{\Delta T}{\Delta z}$$

where:

Y = Young's modulus of steel
a = tube radius
α = thermal expansion coefficient
ω = thickness of tube wall
L = tube section length (fixed support to bellows)
$\Delta T/\Delta z$ = thermal gradient across tube
F = force (cantilevered end)

For the beam tube, this evaluates to $F(\Delta T) = (52kg/°C)\Delta T$. The allowable forces and corresponding ΔTs are provided in Table B-1.

Table B-1: Beam tube support transverse forces and temperature differences

	Allowable Load[1] (kg)	ΔT °C
Horizontal loads:		
Fixed support	584[2]	5.6
Guided support (total capacity, = 2F)	698[2]	6.7
Vertical loads[3]:		
Fixed support	4535[4]	43
Guided support (total capacity, = 2F)	3230[5]	31

[1] From D950029, rev. B

[2] Seismic plus thermal components

3For the case where the top side is warmer than bottom, lifting the dead weight from the fixed support (when the bottom side is warmer, the tube is nearly unconstrained)

[4] Dead load component (3410 kg) plus pullout strength of attachment bolts (est. 1125 kg)

5Dead load plus thermal components