AN EXPERIMENT TO SIMULATE THE HEAT TRANSFER PROPERTIES OF A DRY, HORIZONTAL SPENT NUCLEAR FUEL ASSEMBLY

by

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B.N.E., Nuclear Engineering
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(1986)

SUBMITTED TO THE DEPARTMENT OF
NUCLEAR ENGINEERING
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF

MASTER OF SCIENCE IN NUCLEAR ENGINEERING

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

August 1991

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Department of Nuclear Engineering
August 9, 1991

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ABSTRACT
Nuclear power reactors generate highly radioactive spent fuel assemblies. Initially, the spent fuel assemblies are stored for a period of several years in an on-site storage facility to allow the radioactivity levels of the assemblies to decay. As the radioactive fission product isotopes in the fuel decay, they generate significant amounts of thermal energy producing high temperatures in the spent fuel. The spent fuel from nuclear power plants will eventually have to be transferred to a federal geologic repository in a spent fuel transportation casks. The purpose of this research project is to characterize the relative importance of the heat transfer mechanisms of radiation, conduction, and convection in a dry horizontally-oriented nuclear spent fuel assembly, for eventual application in spent fuel transportation cask design.

To determine the relative importance of each heat transfer mode, an experiment was designed and operated to characterize the heat transfer in an 8x8 square heater rod array (similar to a Boiling Water Reactor fuel assembly) in a horizontal orientation. The experimental apparatus was operated with the following variable parameters and their ranges: Power to Heater Rods (Controlling Temperatures from 40°C to 250°C); Heater Transfer Medium (Air, Nitrogen, Argon, and Helium); Pressure of the Heat Transfer Medium (15 psig, 0 psig, 24 inches of mercury); Power to Boundary Condition Box (not controlled). The experiment was designed, fabricated, and operated under the Sandia National Laboratories-approved MIT Nuclear Engineering Department Quality Assurance Program developed in this work specifically for this project.

The test data obtained from the experimental apparatus was analyzed with the lumped k_{eff}/h_{edge} model developed by R.D. Manteufel at MIT, in related work on this research project, and the Wooten-Epstein relationship developed at Battelle Memorial Institute. The test data was used to validate the lumped k_{eff}/h_{edge} model. Good agreement was found between the lumped k_{eff}/h_{edge} model and the test data in each Test Campaign with the exception of Below Atmospheric Pressure data. The difference is believed to be due in part to the underestimate of the importance of convective heat transfer in the lumped k_{eff}/h_{edge} model but the full reason for the deviation is not known.

Thesis Supervisor: Dr. Neil E. Todreas
Title: Professor of Nuclear Engineering

ACKNOWLEDGEMENTS

This thesis was performed under appointment to the National Academy for Nuclear Training Fellowship program administered by Institute of Nuclear Power Operations (INPO) and research assistantship administered by M.I.T. with funding provided by Sandia National Laboratories. I would like to thank both of these organizations for providing the funding for me to continue my education.

I would like to thank Professor Neil Todreas, my thesis supervisor, for his assistance and supervision over the last year in completing this thesis research. Additionally, my appreciation and admiration go to Professor Peter Griffith, my thesis reader, for his availability in the lab and his light-hearted supervision and guidance.

My deepest appreciation goes to Stefan Chmielewski and Steve Friedenthal, two undergraduate students who worked with me on the project. Their friendship and intelligence showed that teamwork is a great concept and produces a successful experiment. I would also like to recognize F. Jay Bennett and Randy Manteufel.

My undying debt goes to the people who were generous in loaning equipment to me for the experiment: Professor Ronald Ballinger for data acquisition computer equipment; Professor Mujid Kazimi and Tony Hechanova for vacuum equipment; and the guys in the Machine Shop in Building 3, "Tiny," Norm, and Bob for wrenches to drills to lifting hoists to themselves. And lastly to Pete Stahle for always being there when I had questions. The experiment would not have been the same without you.

In addition to the support received at M.I.T. on the project, I would also like to thank those who helped all the way from Albuquerque. At Sandia, my thanks go to Glenn Hohnstreiter, Nisa Brown, Dick Baehr, Jaime Moya, and Joe Koski for your involvement and helpful suggestions. I am especially grateful to Nisa for her integrity, honesty, faith, and friendship.

I give my deepest thanks to Professor Jeffrey Freidberg for having faith in me and giving me the opportunity to succeed.

There are so many people that I have come to admire at M.I.T. To all the folks at the Research Reactor and to the staff in the Nuclear Engineering Department, I will certainly miss you. Particularly, Clare Egan for her amazing resource of information, extremely caring heart, and cheerful disposition; Jennifer deVries Gwinn for her precision and thoroughness; Elenore Kehoe for her professionalism; Paula Cornelio for her humorous anecdotes; Elizabeth Parmelee for her class; David Lewis for his energy and humor; and Laura Miltner for her charm.

And most of all, I would like to thank my parents for always telling me that I can be or do anything I want. I would not be the person I am today without your love and support. To my husband, Bill Hollaway, it has been a challenge for both of us to complete our theses at the same time, but it proves that we can get through anything together. And being together is all that matters. I love you. Lastly, to those furry creatures at home, Kitty and "My Boy Clarence" (a.k.a. Colt), I owe my sanity. I am always amazed how much comfort you give me.

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LIST OF NOMENCLATURE

ANSI	American National Standards Institute
AP	Administrative Procedure
ASME	American Society of Mechanical Engineers
AWG	American Wire Gauge
BWR	Boiling Water Reactor
CFR	United States Code of Federal Regulations
CSDP	Cask Systems Development Program
DOE	United States Department of Energy
IN HG	Pressure Below Atmospheric in Inches of Mercury
MIT	Massachusetts Institute of Technology
NED	Nuclear Engineering Department
NIST	National Institute of Standards and Technology
NPT	National Pipe Threads
OCRWM	US DOE Office of Civilian Radioactive Waste Management
PD	Program Directive
PSIG	Gauge Pressure
PWR	Pressurized Water Reactor
QA	Quality Assurance
QAPP	Quality Assurance Program Plan
QL1	Quality Level 1 (defined in MIT NED AP-5.6 in Appendix A)

QL2	Quality Level 2 (defined in MIT NED AP-5.6 in Appendix A)
QL3	Quality Level 3 (defined in MIT NED AP-5.6 in Appendix A)
SNL	Sandia National Laboratories
TP	Test Procedure
UL	Underwriters Laboratories

CHAPTER 1: INTRODUCTION

1.1 PURPOSE AND SCOPE

Nuclear power reactors generate highly radioactive spent nuclear fuel assemblies. Initially, the spent fuel assemblies are stored for a period of several years in an on-site storage facility, typically a water filled pool, to allow the radioactivity levels of the assemblies to decay. As the radioactive fission product isotopes in the fuel decay, they generate significant amounts of thermal energy producing high temperatures in the spent fuel. The spent fuel from nuclear power plants will eventually have to be transferred to a federal geologic repository via spent fuel transportation casks. Drawings of a typical spent fuel transportation cask, a Boiling Water Reactor (BWR) fuel assembly, and a Pressurized Water Reactor (PWR) fuel assembly are shown in Figures 1-1, 1-2, and 1-3, respectively. These casks and the spent fuel assemblies inside them are shipped in a horizontal configuration. One of the key limiting factors in the design of a horizontal spent fuel cask is heat dissipation. The maximum centerline temperature of the spent fuel assemblies in the cask limits the total amount of fuel which can be loaded in a transportation cask. The centerline temperature requirement requires spent fuel to be cooled at the generating reactors in on-site spent fuel pools for an extended period of time. Current methods of calculating maximum centerline temperatures of dry horizontal spent fuel assemblies have assumed that only radiation and conduction heat transfer mechanisms are important contributors. These calculations have typically neglected any

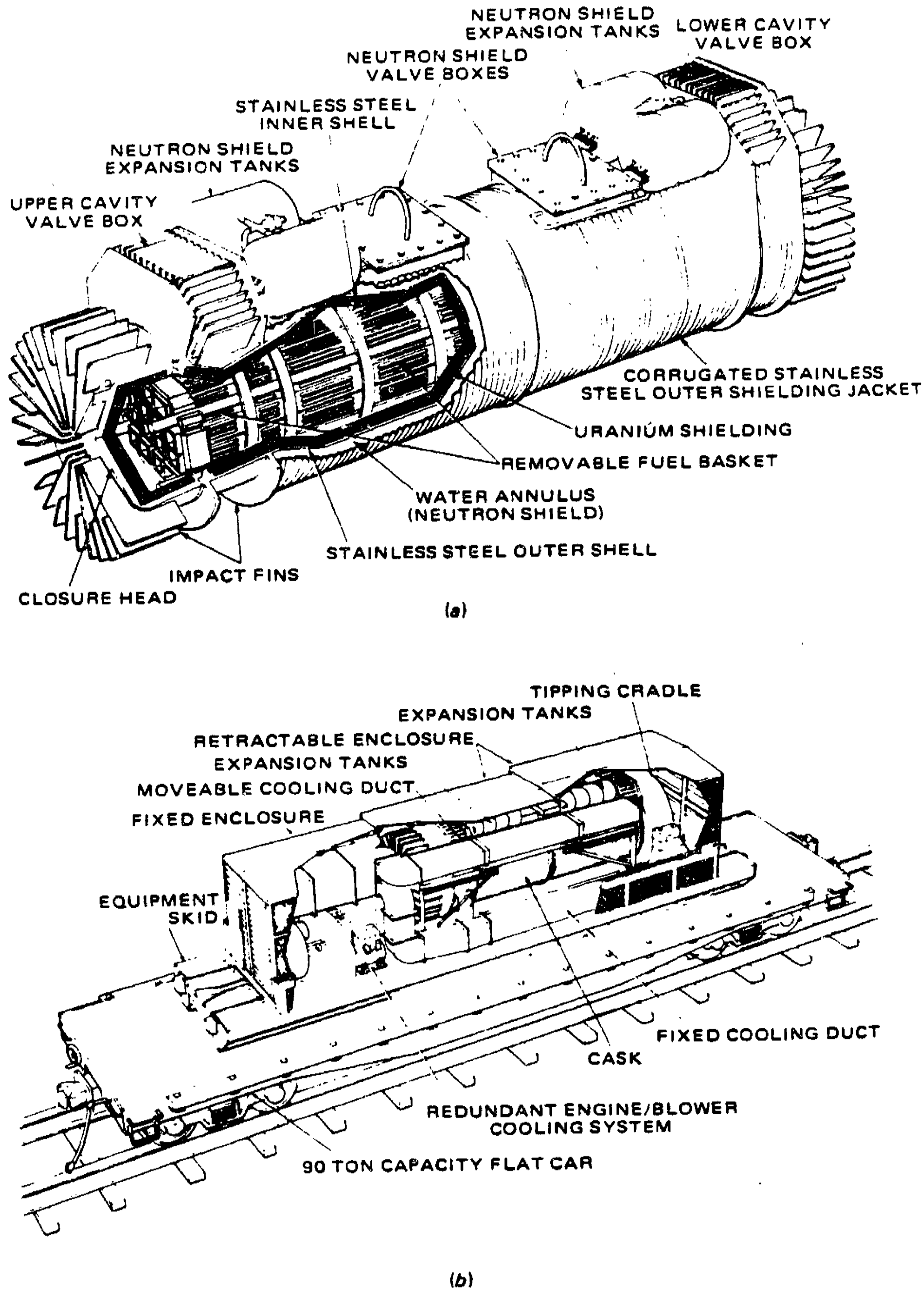

Figure 1-1: Typical Spent Fuel Transportation Cask
(GE IF-300 (a) separate, and (b) in normal rail-transport configuration) [K-1]

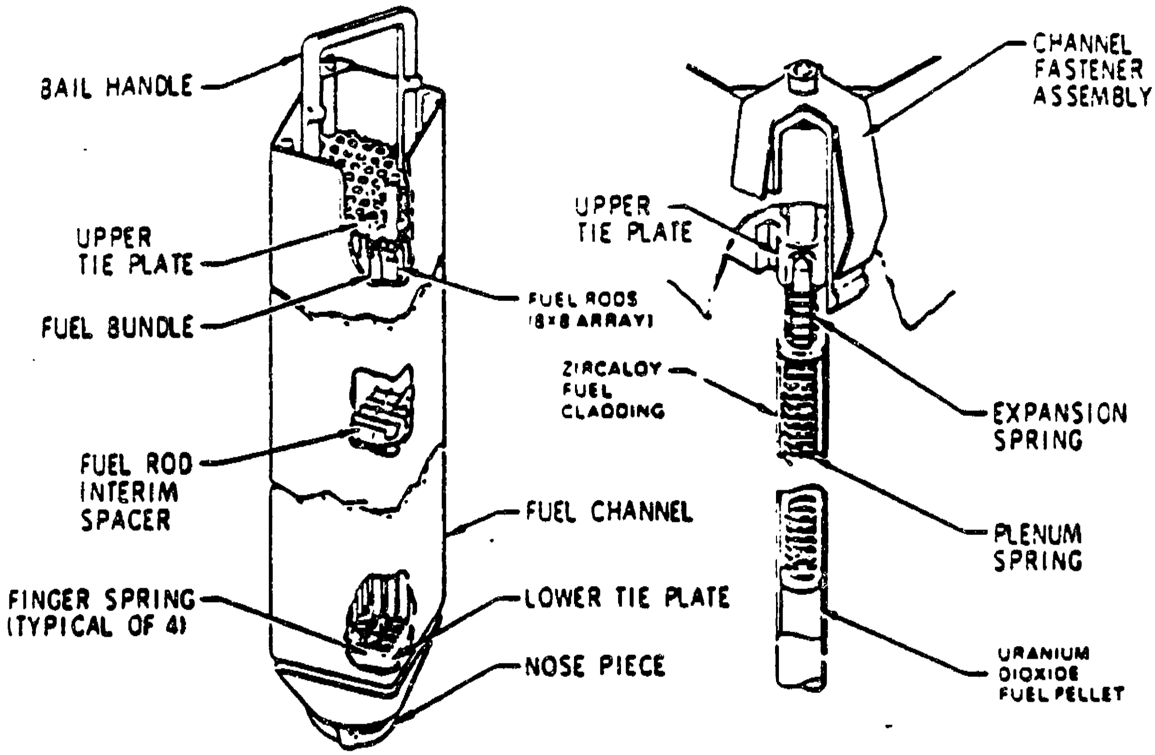

Figure 1-2: Typical Boiling Water Reactor (BWR) Fuel Assembly [K-1]

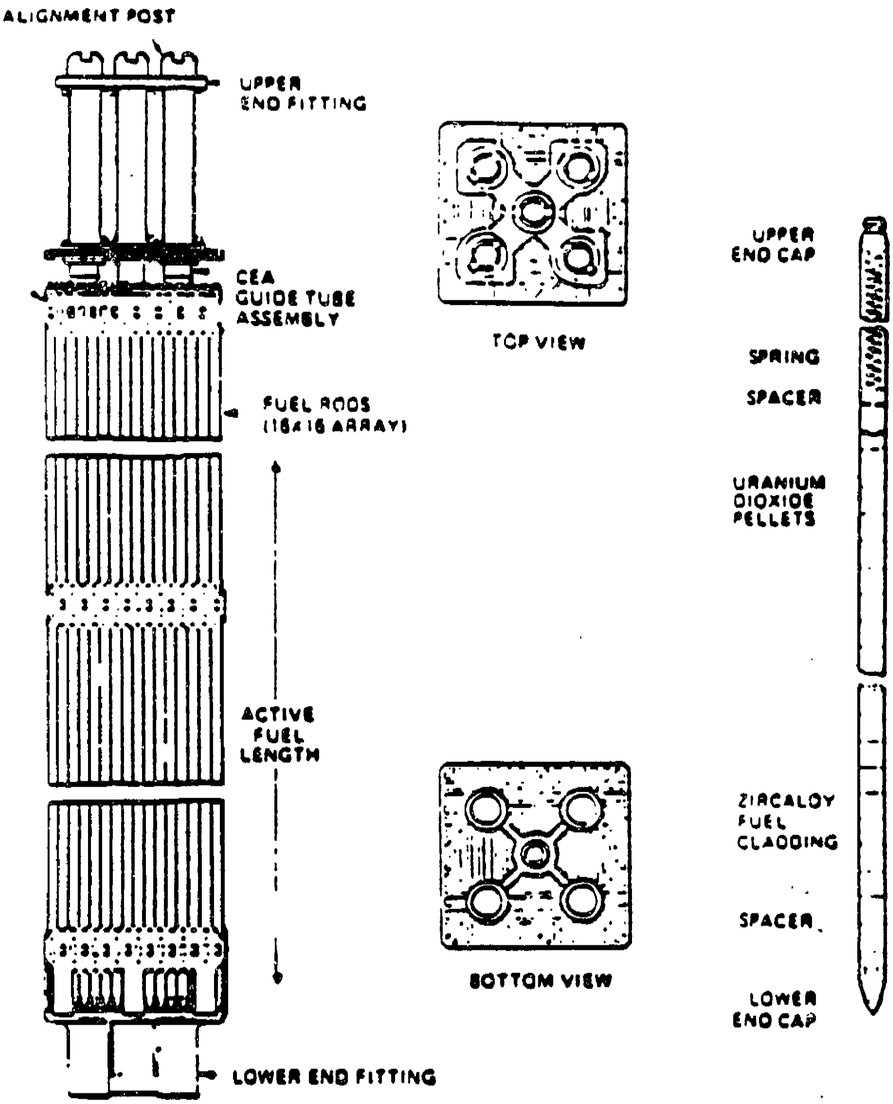

Figure 1-3: Typical Pressurized Water Reactor (PWR) Fuel Assembly [K-1]

contribution from natural convection heat transfer. The purpose of this research project is to characterize the relative importance of radiation, conduction, and convection in a dry horizontally-oriented nuclear spent fuel assembly. With this information, future transportation cask designs can be designed to accommodate more spent fuel and higher heat load per assembly of spent fuel, and current generation transportation casks will be able to hold higher thermal power spent fuel (which means less cooling time in the spent fuel pool) while still meeting the maximum centerline temperature constraints stated in the Code of Federal Regulations Title 10 Part 71 "Packaging and Transportation of Radioactive Material" [C-1].

1.2 BACKGROUND

Experimental work to simulate the heat transfer in a dry, horizontal nuclear power reactor spent fuel assembly has been the focus of several previous research projects. A complete literature review for experimental and theoretical heat transfer in an enclosed rod array was performed by R.D. Manteufel in his PhD Thesis at the Massachusetts Institute of Technology, 1991 in related work for this research project [M-1]. Experiments using electrically heated rods configured in a horizontal square array have been carried out by J.S. Watson at Oak Ridge National Laboratory in 1963 [W-1], R.L. Cox in a PhD Thesis at the University of Tennessee-Knoxville in 1976 [C-2], and Kyung-Jin Choi in a PhD Thesis at the University of Wisconsin-Madison in 1983 [C-3]. However, each of these previous works has concentrated on only one heat transfer mechanism.

The work on this research project is aimed at formulating a unified overall model of heat transfer. The goal of current research work by Sandia National Laboratories, of which this thesis is a part, is "to develop a fundamental understanding of the heat transfer mechanisms in a dry horizontally-oriented nuclear spent fuel assembly," and to characterize "the magnitude of thermal conductance offered by radiation, conduction, and convection" and the relative importance of each heat transfer mode [S-1]. This thesis work designed and operated an experiment to simulate the heat transfer characteristics of an 8x8 square heater rod array (similar to a Boiling Water Reactor fuel assembly), and recorded the temperatures inside the heater rods at a variety of power levels. The reduced data from this experiment has been utilized to verify a model developed to predict the maximum pin surface temperature in a fuel assembly and to characterize the relevant heat transfer mechanisms in a fuel assembly. This model was developed by R.D. Manteufel in his PhD Thesis at the Massachusetts Institute of Technology, 1991 in related work for this research project [M-1].

1.3 ORGANIZATION OF THIS WORK

Chapter 2 presents the Quality Assurance Program developed at MIT for this research project. The Program was developed to provide a high level of confidence that the experimental system or individual components will perform satisfactorily in service and that the data recorded from the experiment will be useful and referenceable by outside parties. The Program has been audited by the Sponsor (SNL) and has been deemed effective. The approval process is described in this chapter.

Chapter 3 presents the components of the experimental apparatus individually and as a whole. The design considerations for each major component are addressed.

Chapter 4 discusses the Test Campaigns, procedural processes and general results of the data taken on the experimental apparatus. The Test Campaigns are Atmospheric Pressure Testing in Air, Above Atmospheric Pressure Testing in Different Fill Gases, Below Atmospheric Pressure Testing, and Specific Testing that was not originally identified and was deemed necessary as testing progressed. The variable parameters in the Test Campaigns and the procedural processes for data acquisition are also discussed.

Chapter 5 presents the overall scheme of analysis/reduction of the data taken in each Test Campaign. The test data is used in this chapter to verify an effective conductivity model developed by R.D. Manteufel in related work on this research project

[M-1]. Section 5.2 presents the process for reduction of Air and Nitrogen data. An error analysis of the experimental data is also provided.

Chapter 6 summarizes the experimental design, fabrication, and quality of the experiment and the data acquired in test runs of the experiment. This chapter also provides recommendations for future work.

Appendix A contains the most recent revision (as of August 9, 1991) of the MIT Nuclear Engineering Department Quality Assurance Program Plan and Administrative Procedures developed for this experiment.

Appendix B contains the pertinent MIT Quality Documents referenced in this thesis.

Appendix C contains the analysis for the selection of the length and thickness of the Heater Rods used in the experiment.

Appendix D contains the data acquisition computer code for the experimental apparatus.

Appendix E contains the experimental data presented on formatted data sheets for each Test Campaign.

Appendix F contains the process of data reduction for the data taken above atmospheric pressure in Helium and in Argon and the data taken below atmospheric pressure.

Appendix G contains the computer code and its results for determining the experiment's end heat losses for correction of the experimental data.

CHAPTER 2: QUALITY ASSURANCE PROGRAM

2.1 INTRODUCTION

Prior to assembly of the experimental apparatus, a Quality Assurance Program was developed at MIT by the author as imposed by Sandia National Laboratories (SNL) in June 1990. The requirement was imposed by SNL to satisfy their Cask Systems Development Program (CSDP) Quality Assurance Program Plan (QAPP) [S-2]. Their plan states the ultimate objective of the program as follows:

> "The objective of the Department of Energy's (DOE) Office of Civilian Radioactive Waste Management (OCRWM) Cask Systems Development Program is to design, develop, fabricate, test and certify a family of prototypical casks to be used to transport spent nuclear fuel and high-level radioactive waste to Federal facilities in a national system for disposal of such waste in accordance with the Nuclear Waste Policy Act. Prototype casks will be designed to minimize life cycle costs and fabricated and tested to ensure acceptability for the eventual cask fleet."

The certification and acceptability of this experimental research is derived through the development and implementation of a Quality Assurance (QA) Program. The QA Program is required to provide a high level of confidence that the experimental system or individual components will perform satisfactorily in service and that the data recorded from the experiment will be fully useable and referenceable by outside parties.

2.2 MIT NUCLEAR ENGINEERING DEPARTMENT QA PROGRAM

The MIT Nuclear Engineering Department (NED) Quality Assurance Manual was developed to fulfill the QA requirements imposed by SNL. The MIT NED QA Manual contains the most recent revisions of the MIT NED Quality Assurance Program Plan (QAPP) [M-2] and the MIT NED Administrative Procedures (APs) [M-3]. The MIT NED QAPP dictates general quality requirements for this experimental research. The processes of implementing these general quality requirements are documented in the MIT NED APs. The latest revision to the MIT NED QA Manual (as of August 9, 1991) is provided in Appendix A.

The major points of the MIT NED QA Program will be discussed in this section. They are:

(1) Identification of a Quality Level of Effort,

(2) Documentation of Activities Performed,

(3) Retention of Documents,

(4) Calibration of Measuring and Test Equipment,

(5) Inspection of Activities Performed, and

(6) Certification and Training of Personnel.

The MIT NED QA Program has a tri-level Quality Assurance System to allow identification of the appropriate quality level for any task performed by its degree of risk to public radiological health and safety. Quality Level 1 (QL1) is the most stringent level. It should be assigned to activities when error could directly impact public radiological health and safety. Quality Level 2 (QL2) should be assigned to activities with an indirect relationship to adverse radiological effects, such as, an error or failure which could lead to circumstances that would require a QL1 item to perform its safety function. Quality Level 3 (QL3) is the least stringent level of quality. It is selectively assigned for importance other than radiological safety. Further details regarding each Quality Level can be found in MIT NED AP-5.6, "Quality Program Levels of Effort," in Appendix A.

The Quality Level of Effort for this research project is QL2. MIT NED AP-5.6 Appendix C "Quality Level Assignment Checklist" was completed for this research project, as a whole, to determine the most stringent Quality Level that could ever be assigned to any individual project task. QL2 was assigned to all project tasks and requires full compliance with the MIT NED QAPP and APs. This level was not recorded on individual documents but is the understood level as documented in the Lovett to Todreas Memorandum of Understanding dated April 2, 1991 regarding "Project Tasks Quality Level" [L-1]. A copy of this Memorandum of Understanding is provided in Appendix B. This research project could indirectly impact the design of the heat removal capabilities or thermal safety features of a transportation cask.

The MIT NED QA Program requires documentation of activities or tasks performed for this research project. If tasks are repetitive, they should be performed with approved procedures to ensure the task is controlled and performed consistently. Operating logs are also an acceptable form of documenting activities. If a nonconformance exists, it should be reported and resolved as discussed in MIT NED AP-5.8, "Control of Nonconformances." Resolution of a nonconformance may be by repairing the item, replacing the item, or accepting the item as-is. Additionally, the MIT NED QA Program requires retention of Quality Documents to demonstrate that tasks have been done completely and correctly. Document retention also provides task traceability during the project and for future verification.

The MIT NED QA Program requires that measuring and test equipment be calibrated and "this calibration shall be directly traceable to the National Institute of Standards and Technology (NIST) primary standards" [M-2]. Calibration with traceability to NIST standards is required to ensure conformance of instrumentation to the manufacturer's specified tolerances. This conformance ensures the reliability of the test data. Calibration is procedurally controlled to ensure each instrument used has a current calibration with an expiration date affixed to the front of the instrument where possible and provides a means to restore an out-of-calibration instrument back into calibration or control. Certification is a quality record.

The MIT NED QA Program requires inspection of activities performed to verify quality. Inspection includes task verification to ensure that a task was performed correctly and receipt inspection to ensure a procured item conforms to procurement specifications. Any inspection performed is required to be documented as directed in MIT NED AP-2.10 "Inspection" and is a quality record.

The MIT NED QA Program requires certification and training of personnel to ensure each individual has an acceptable understanding and knowledge of tasks they are assigned to perform. Training includes continuous familiarization with the Quality Program, job responsibilities and authority relating to QA, and qualification for special tasks on the basis of education, experience, and proof of principle. Certification and training are required to be documented and retained as a quality record.

Details regarding sponsor approval of this QA Program are provided in the following section.

2.3 PROGRAM APPROVAL BY SANDIA NATIONAL LABORATORIES

On October 19, 1990, the MIT NED QAPP (Revision A) was approved by MIT and issued to SNL for review and approval. The program was written to closely emulate the SNL CSDP QAPP [S-2]. On December 17, 1990, the MIT NED QAPP was conditionally approved by SNL's Division 6320 QA Coordinator, Mr. Richard M. Baehr [S-3]. On January 25, 1991, Mr. Baehr's concern was resolved by MIT's commitment to revise the MIT NED QAPP [M-4]. A copy of each of these letters is provided in Appendix B.

During the week of March 25, 1991, Revision B to the MIT NED QAPP and Revision A to the MIT NED Administrative Procedures (APs) were approved and issued to Controlled Document Holders as the MIT NED QA Manual with an effective date of April 1, 1991. The MIT NED APs were written to closely emulate applicable SNL CSDP Program Directives (PDs) [S-4].

On April 4, 1991, a SNL representative, Mr. Richard M. Baehr, audited the MIT NED QAPP and APs for effectiveness. Shortly thereafter in early April 1991, MIT was formally notified through the Quality Assurance Audit Report for SNL Audit No. MIT-A91-1 [S-5] that the MIT QA Program is effective and satisfied the QA requirements for SNL Contract 42-5638 [S-1]. As written in the cover letter from Mr. Baehr dated April 9, 1991, "there were no reported Audit Findings or Observations and Audit MIT-A91-1 is closed out" [S-6]. A copy of Mr. Baehr's letter and SNL Audit No. MIT-A91-1 is provided in Appendix B.

During the month of May, the MIT NED QA Program documents were reviewed and revised. The Program was modified to remove specific reference to SNL so that the Program could be applied to any research project at MIT. MIT NED QAPP Revision C and Revision B to 12 MIT NED APs were issued and distributed to Controlled Document Holders on May 28, 1991.

During the month of July, several MIT NED APs were revised to remove reference to the QA Coordinator by name. Revision B to 2 MIT NED APs and Revision C to 4 MIT NED APs were issued and distributed to Controlled Document Holders on July 31, 1991.

2.4 CHAPTER SUMMARY

As required by Sandia National Laboratories' Cask Systems Development Program Quality Assurance Program Plan, a Quality Assurance Program was developed and implemented for this research project. The QA Program was audited by a SNL representative and has been deemed effective. The MIT NED QA Program documents are written in a format that can be applied to any experimental research project at MIT.

CHAPTER 3: EXPERIMENTAL APPARATUS - DESIGN AND CONSTRUCTION

3.1 INTRODUCTION

The conceptual design of each experimental component was chosen to emulate an actual 8x8 Boiling Water Reactor (BWR) spent fuel assembly and its containment in a transportation cask. To ensure the design would work, a proof of principle experiment was constructed and tested. The proof of principle experiment was a 4x4 square array of electrically heated rods five feet in length with a pitch to diameter ratio of 1.3 placed in a galvanized steel box contained in a metal tube assembly. Each major component, from the heater rods to the containment vessel, was constructed in-house. Additional information and experimental results from the proof of principle experiment can be found in F. Jay Bennett's Bachelor of Science thesis, "An Experimental Study of Thermal Radiation and Convection in a Horizontal Spent Fuel Cask," June 1990 [B-1].

There are several lessons learned from the proof of principle experiment that were incorporated into the 8x8 square array experiment. The lessons learned are that: (1) for the tolerances of each component to be precise and quantifiable, the experiment's components should be fabricated by professional manufacturers with working Quality Assurance Programs, and (2) for the recorded results from the instrumentation to be reliable and referenceable, the instruments should be calibrated and certified to NIST standards. These lessons learned were incorporated into the 8x8 experiment through the development and implementation of the MIT NED Quality Assurance Program Plan and Administrative Procedures.

Chapter 3 presents a description of the major components of the experiment. The major components are:

(1) the Heater Rods;

(2) the Rod Support Plates;

(3) the Boundary Condition Box;

(4) the Containment Vessel; and

(5) the Instrumentation and Control Equipment.

This chapter also describes the assembly of the Experimental Systems and identifies each item with a unique identification label by the item's system, function and a sequential number of similar items in the system as directed by MIT NED Administrative Procedure 2.9 "Handling, Storage and Shipping." A copy of MIT NED AP-2.9 is provided in Appendix A.

3.2 HEATER RODS

The Heater Rods are special order cartridge heaters manufactured by Watlow Electric Manufacturing Company in St. Louis, Missouri. The manufacturer's code number is G24AX58A. The manufacturer's drawing of a Heater Rod is provided in Figure 3-1; and a list of Heater Rod's as-built specifications is provided in Table 3-1. Note that these specifications in Table 3-1 are less restrictive than the specifications provided in Figure 3-1. This difference is due to the difficulty in fabricating the rods to the tolerances shown in Figure 3-1. Table 3-1 lists the acceptable specifications and tolerances as agreed upon with the manufacturer.

The Heater Rods are 0.375 inch diameter, 24.5 inch long copper sheathed electric-resistance cartridge heaters with a 23.5 inch nickel-chromium conductor wire heated region and a type K thermocouple (Chromel, (+) lead; and Alumel, (-) lead) located at the centerline of the Heater Rod insulated in compacted magnesium oxide [W-2]. The maximum operating temperature of the heater rods is 370°C. Each individual Heater Rod is rated for a maximum capacity of 30 Volts/150 Watts; however, per the manufacturer, these specifications may be exceeded to a limited degree. The limiting factor is the power density delivered to each Heater Rod. This limit is 44 Watts per square inch. With the assembled electrical configuration of the Heater Rods, the Heater Rods could be operated with 120 Volts/600 Watts. The heater rods are electrically configured with 4 parallel sets of 16 heater rods in series as shown in Figure

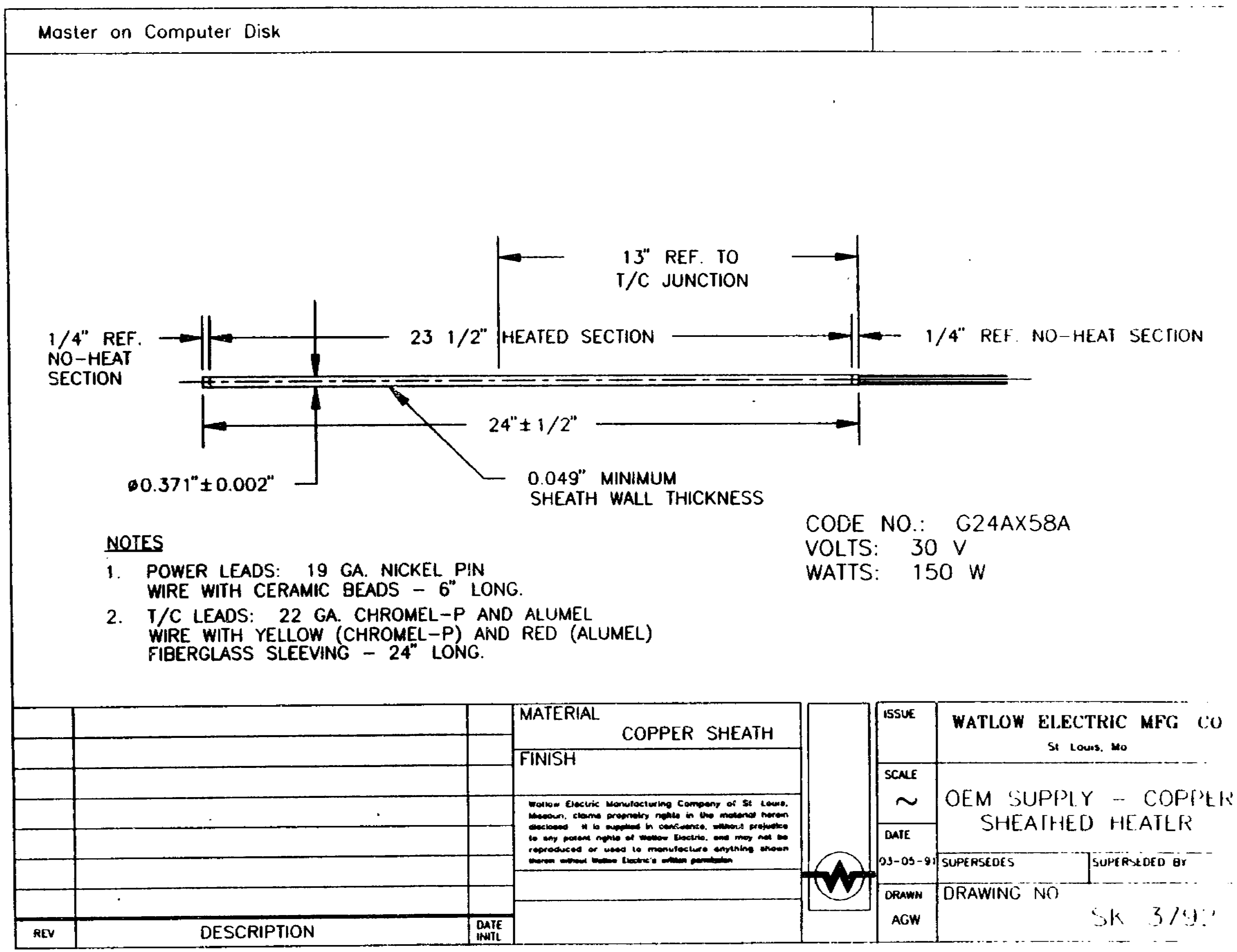

Figure 3-1: Engineering Drawing of a Heater Rod

Table 3-1: List of Heater Rod Specifications

Physical Description:

The Heater Rods are 0.375 inch diameter, 24.5 inch long copper sheathed electric-resistance cartridge heaters with a 23.5 inch nickel-chromium conductor wire heated region and a type K thermocouple (Chromel, (+) lead; and Alumel, (-) lead) located at the centerline of the Heater Rod insulated in compacted magnesium oxide.

Specifications:

Material	Copper sheath
Minimum Sheath Thickness	0.049 inch
Length	24.5 inches ± 0.5
Diameter	0.375 inch ± 0.004
Maximum Operating Temperature	370°C
Internal Thermocouple Location	11.5 inches ± 0.5 (from the non-lead end)
Type K (Alumel/Chromel) Thermocouple Wire Resistance	4.7 Ω ± 0.4
Power Lead Resistance (cold)	5.7 Ω ± 0.3
Volts	30 Volts per rod
Watts	150 Watts per rod
Power Density	44 Watts per square inch

3-2. In future purchases, the Heater Rods should be specified to operate at 120 Volts/600 Watts individually. This change would give more flexibility when electrically configuring the Heater Rod array.

The Heater Rods were ordered and received prior to the development and implementation of the MIT NED Quality Assurance Program. To ensure the quality of the Heater Rods before use, each Heater Rod was inspected and assigned a unique identification number. The Heater Rods were inspected in eight full sets of nine Heater Rods each and one partial set of four Heater Rods. Each set was given an alphabetic identifier and then each rod in the set was assigned a numeric identifier from 1 to 9 (example: A-2 is the second rod inspected in Set A). The purpose of the inspection was to ensure each Heater Rod's physical characteristics were within specified tolerances. These characteristics were recorded for each Heater Rod. The inspected characteristics and allowed tolerances are:

Length	24.5 inches	± 0.5	
Diameter	0.375 inch	± 0.004	
Thermocouple Wire	Intact with Chromel and Alumel Wires		
	Resistance	4.7 ohms	± 0.4
Power Leads	Intact with Ceramic Beads		
	Resistance (cold)	5.7 ohms	± 0.3

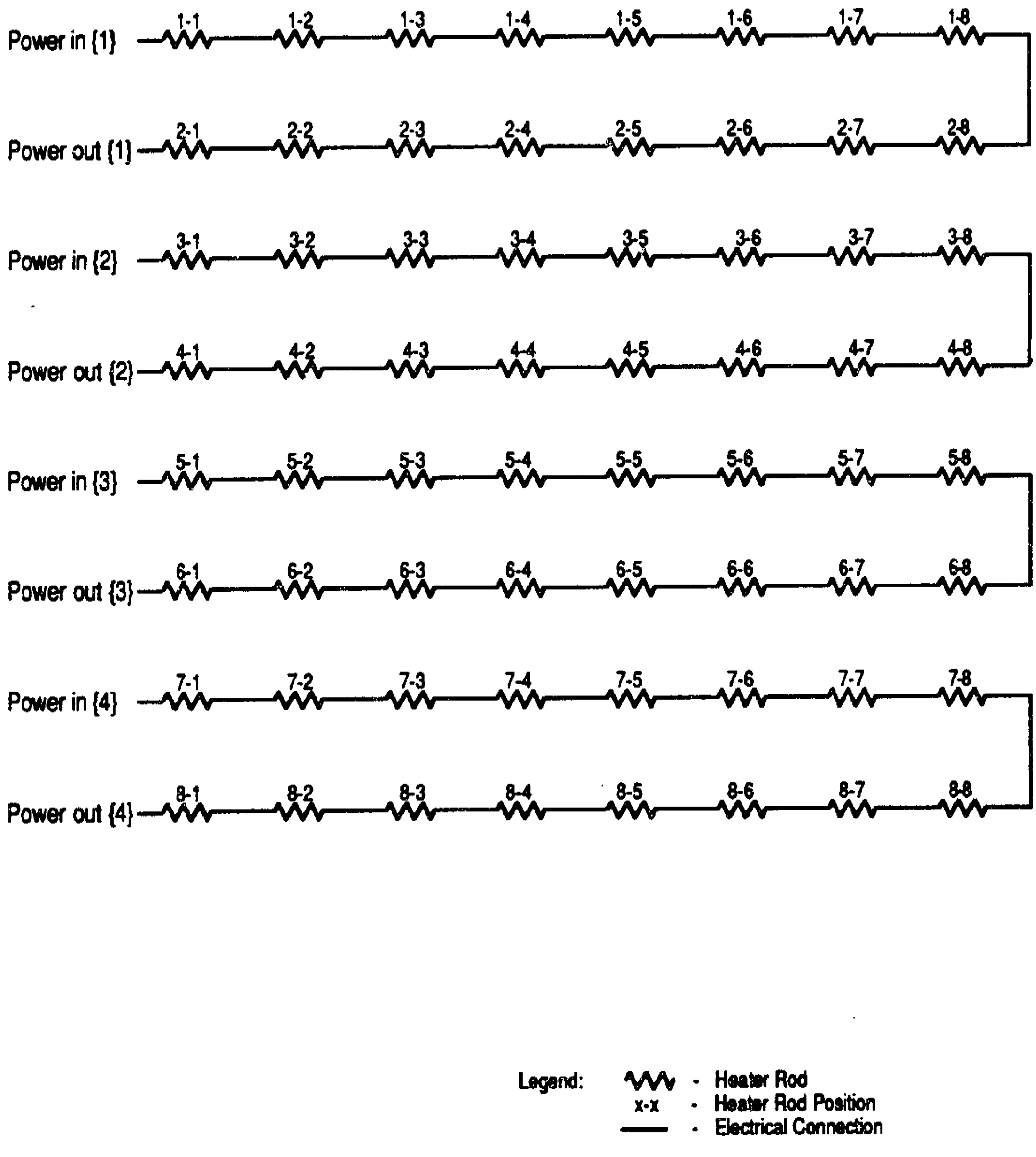

Figure 3-2: Electrical Configuration of the Heater Rods in the Experimental Apparatus

This inspection found ten (10) unacceptable Heater Rods. Eight of these Heater Rods have subsequently been repaired or replaced by the manufacturer. One Heater Rod was destructively tested to ensure that the internal thermocouple was located 11.5 inches (± 0.5) from the non-lead end of the Heater Rod. The thermocouple was located within tolerance; therefore, the remaining unrepaired Heater Rod did not need to be destructively tested.

Additionally, the thermocouples of the Heater Rods were calibrated in-house using externally attached thermocouples that had been calibrated to NIST standards. The thermocouples of a 10% random sampling of the Heater Rods (eight) were calibrated from approximately 0.0°C (Ice Bath) to approximately 300°C (Heated Rods). The thermocouple in each Heater Rod was calibrated at Room Temperature. The acceptable tolerance for these tests was ± 1.8°C. This tolerance was chosen to exceed the calibration tolerances of the NIST certified thermocouples (± 0.6°C) and the NIST certified digital thermometer (± 1.0°C) used during in-house calibration of the internal centerline Heater Rod thermocouples. This tolerance was not exceeded by any of the Heater Rod thermocouples.

The length of the Heater Rods, 24.5 inches, was chosen for several reasons. An analysis was performed by R.D. Manteufel to determine the optimal the length of the Heater Rods accounting for thermal end effects on the centrally located thermocouple and for structural support needed to hold the rods in a pitch to diameter ratio of approximately 1.3. A copy of this analysis is provided in Appendix C. Additionally, the length, 24.5 inches, is the approximate distance between the grid spacers of a typical Light Water Reactor spent fuel assembly [A-1][N-1][P-1][W-3].

The material, copper, and the wall thickness, a minimum of 0.049 inch, of the Heater Rods were chosen to ensure that the exterior rod wall temperature was as uniform as possible. A copy of the analysis for selecting the material and thickness, performed by R.D. Manteufel, is provided in Appendix C. However, the large wall thickness required made the Heater Rod fabrication difficult and caused the final product to be extremely delicate. The swaging process used in Heater Rod construction caused the thermocouple and power wires to neck and become prone to breaking. Seven of the ten defective Heater Rods discovered during the receipt inspection discussed earlier had either disconnected thermocouple and/or power leads. The Heater Rod manufacturer recommended a new minimum wall thickness of 0.025 inch for more durable Heater Rods in future purchases.

These Heater Rods are arranged in an 8x8 square array with a rod pitch to diameter ratio of approximately 1.33 using Rod Support Plates located one inch from each end of the Heater Rods. Figure 3-3 shows the arrangement of the Heater Rods in the 8x8 array identified by their unique identification number. The Rod Support Plates are discussed in Section 3.3.

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Arrangement of Heater Rods
in 8x8 Array

Column

Row	1	2	3	4	5	6	7	8
1	E-6	C-5	I-1	G-7	E-1	H-8	B-4	A-6
2	A-3	G-2	D-9	D-1	G-3	E-4	H-5	D-5
3	A-4	G-8	G-5	F-6	E-8	E-2	D-4	C-9
4	C-2	E-5	F-7	H-3	H-7	A-5	B-2	A-8
5	D-8	D-2	C-6	C-8	C-4	C-1	C-3	D-6
6	E-7	F-9	F-1	F-5	E-9	F-3	F-2	F-8
7	H-9	G-1	H-4	G-6	G-4	G-9	H-6	H-2
8	A-9	B-5	B-1	B-6	B-7	B-3	A-1	B-9

Confirmation Signatures: [illegible signature]

[illegible signature]

Date: 01-21-91

Figure 3-3: Arrangement of Heater Rods in 8x8 Array by Unique Identifying Numbers

3.3 ROD SUPPORT PLATES

The Rod Support Plates are special order machined plates fabricated by Sheffield Progressive, Incorporated in North Reading, Massachusetts. The manufacturer's drawing of the Rod Support Plates is provided in Figure 3-4; and a list of the Rod Support Plates' specifications is provided in Table 3-2.

The Rod Support Plates are two identical 4.5 inch square 1095 Carbon Steel plates, 0.032 inch thick, with an 8 square array of 0.380 inch holes (64 total) centered on each plate. The pitch between the holes is 0.500 inch.

The thickness of the plates, 0.032 inch, was chosen to minimize the amount of heat conducted from the Heater Rods to the plates while still providing adequate structural support for the Heater Rod array. The material, 1095 Carbon Steel, was chosen due to its availability, strength, and low cost.

Due to incomplete delivery of the purchase order by the manufacturer, the Rod Support Plates were initially held as non-useable items until the engineering drawing was received. Upon receiving the drawing, the Rod Support Plates were inspected and found to be acceptable. The QA hold was lifted, and the Rod Support Plates were determined useable on October 24, 1990.

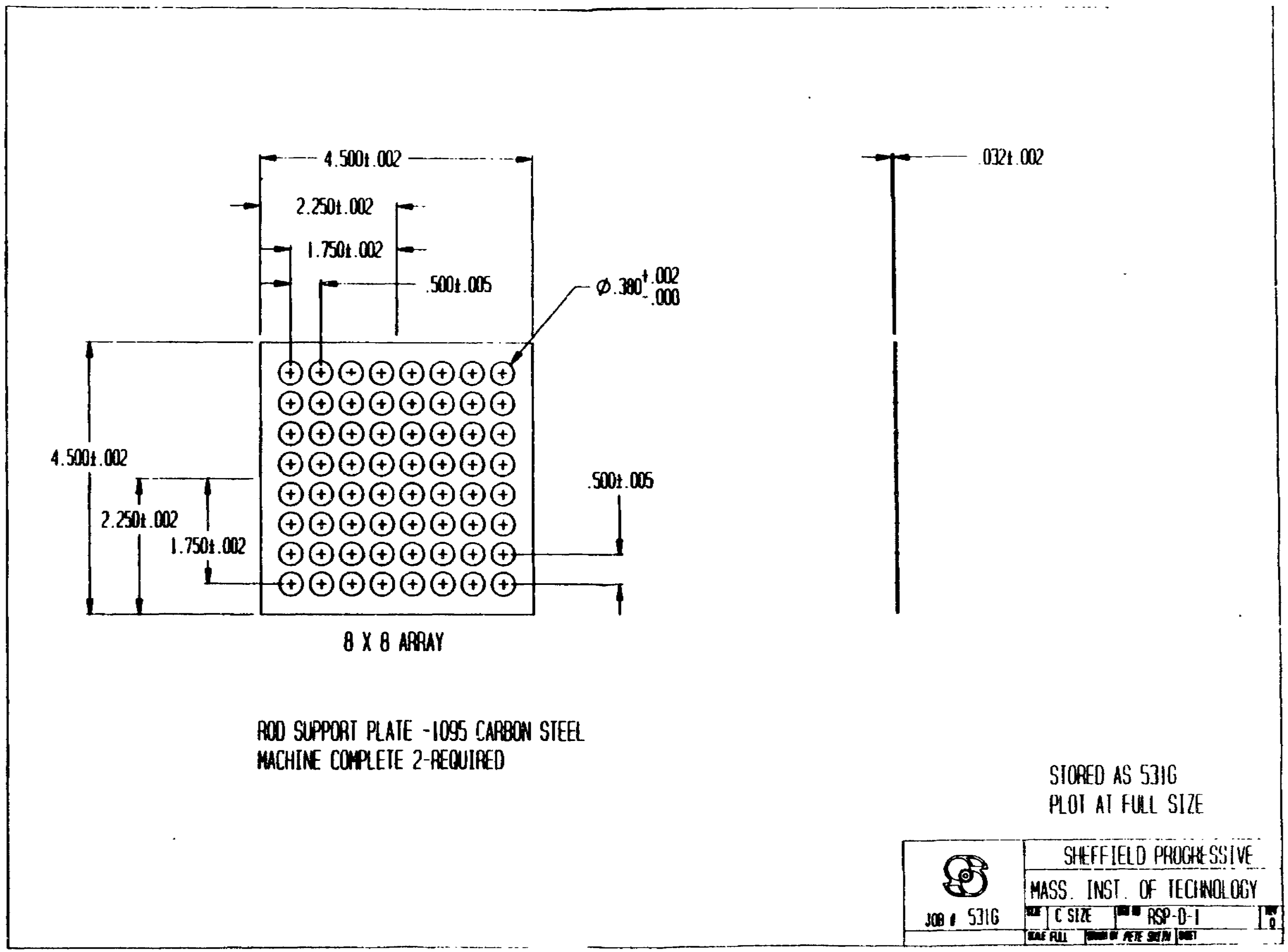

Figure 3-4: Engineering Drawing of the Rod Support Plate

Table 3-2: List of Rod Support Plate Specifications

Physical Description:

Two identical 4.5 inch square 1095 Carbon Steel Plates, 0.032 inch thick, with an 8 square array of 0.380 inch holes (64 total) centered on each plate (center to center between holes is 0.500 inch).

Specifications:

Material	1095 Carbon Steel
Length	4.500 inches ± 0.002
Width	4.500 inches ± 0.002
Thickness	0.032 inch ± 0.002
Array of holes	8 x 8 (total 64 holes)
Diameter of holes	0.380 inch + 0.002, - 0.000
Center to center between holes (Pitch)	0.500 inch ± 0.005
Center hole location	Center of plate ± 0.005

The Rod Support Plates hold the Heater Rods in an 8x8 square array with a pitch to diameter ratio of approximately 1.33. The resulting 8x8 square array of Heater Rods rests in a Boundary Condition Box. The Boundary Condition Box is discussed in Section 3.4.

3.4 BOUNDARY CONDITION BOX

The Boundary Condition Box provides the boundary condition for the Heater Rod array. The box has two components: a metal box known as the Boundary Condition Box Support Structure and the heaters attached to the support structure. These components are discussed individually.

The Boundary Condition Box Support Structure (BCB-SS-1) is a special order machined aluminum box fabricated by Sheffield Progressive, Incorporated in North Reading, Massachusetts. The manufacturer's drawings of the Boundary Condition Box are provided in Figures 3-5 and 3-6; and a list of the Boundary Condition Box's specifications is provided in Table 3-3.

The Boundary Condition Box Support Structure is made from 2 sets of 2 identical 6061 Aluminum pieces. When these pieces are assembled, they form a rectangular box: 6.55 inches square outside with a 1.00 inch wall thickness, 4.55 inches square inside, and 25.00 inches in length. These pieces are held together with removable screws for easy assembly/disassembly. The 6.55 inch wide piece has eight screw holes and the 4.55 inch wide piece has eight screw taps. Sixteen 1.75 inch long screws structurally hold the pieces into the box form. In addition to the assembly screw holes and taps, each piece has four 0.50 inch screw taps for the attachment of strip heaters.

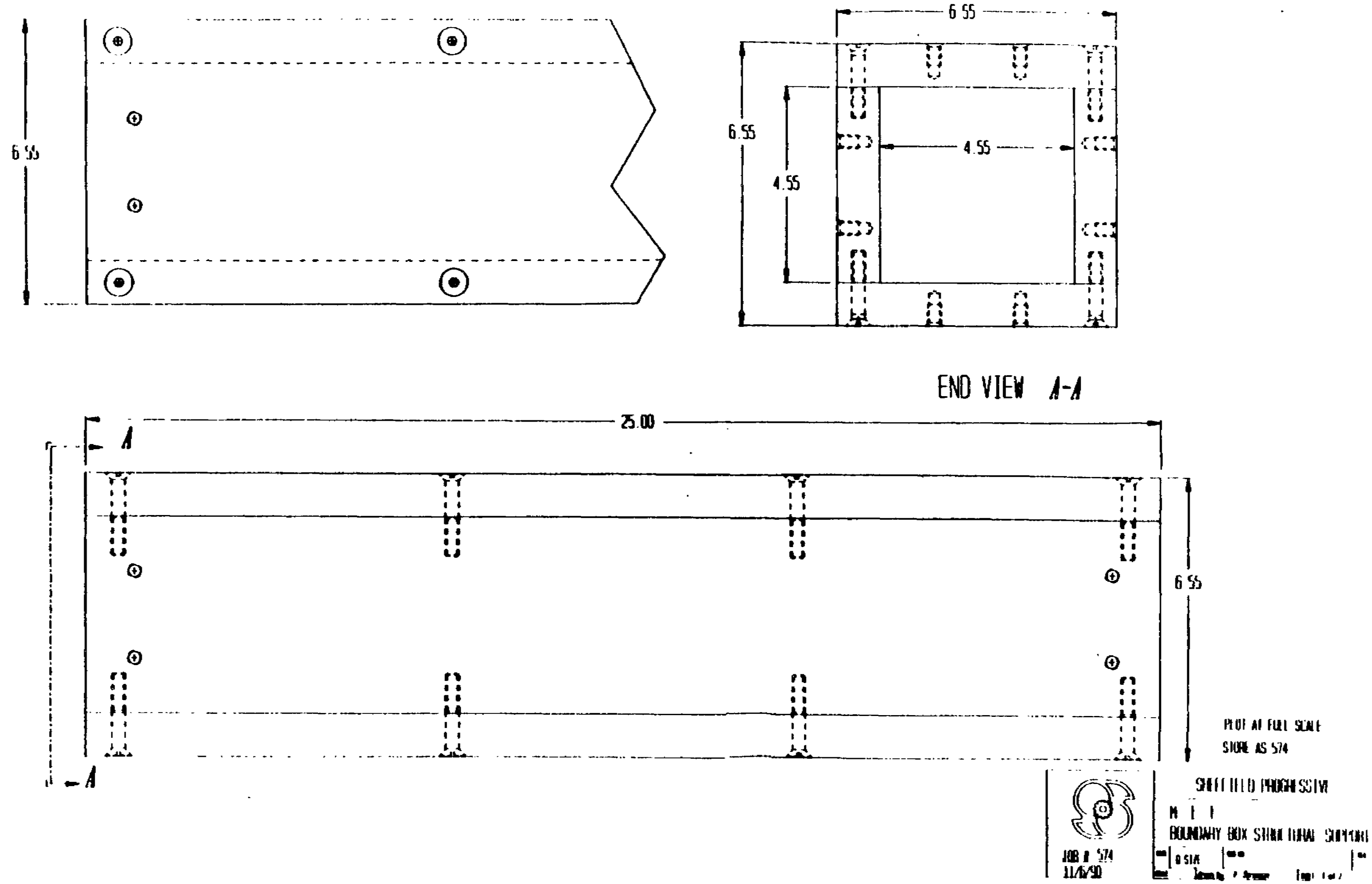

Figure 3-5: Engineering Drawing #1 of the Boundary Condition Box

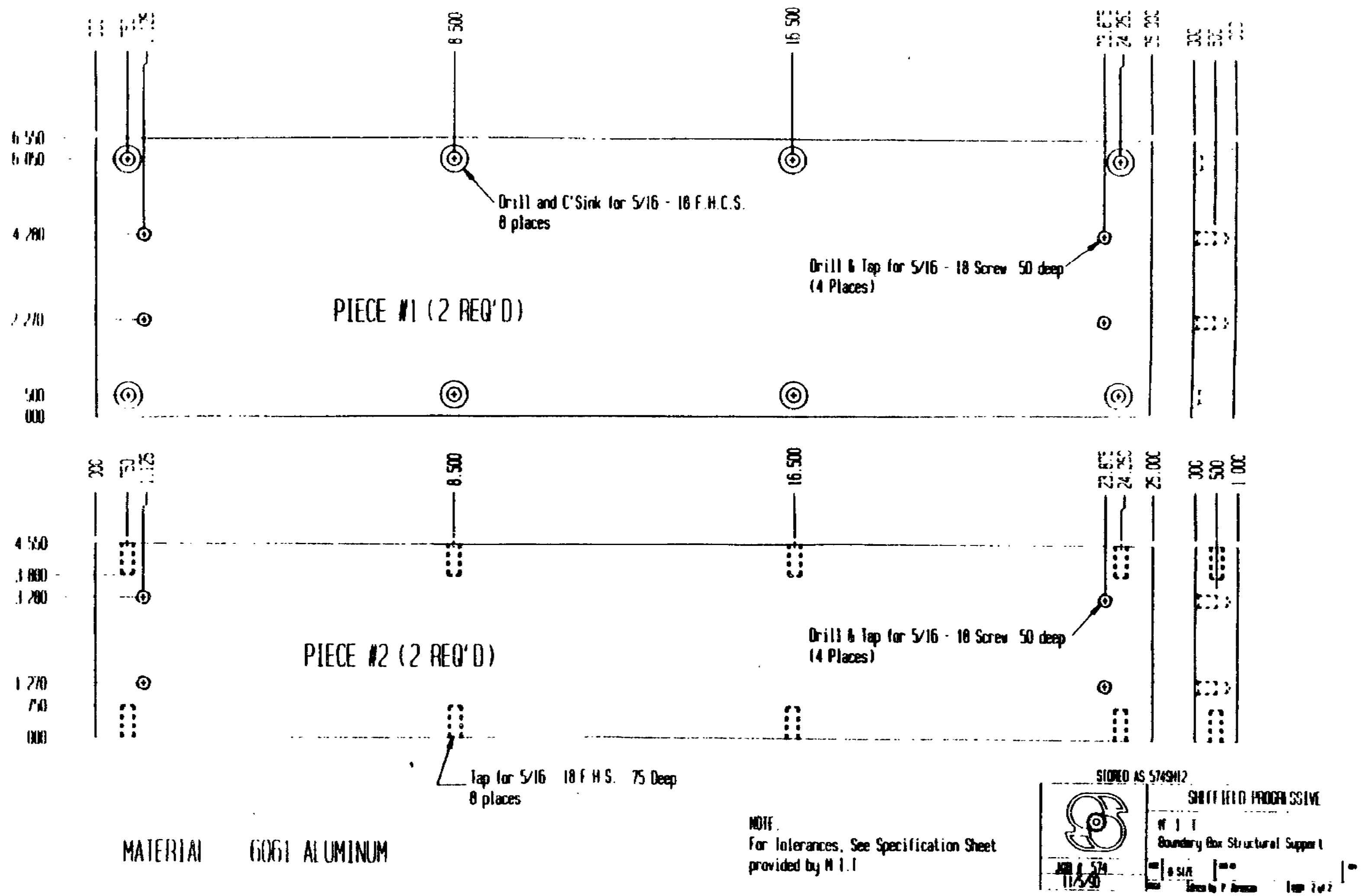

Figure 3-6: Engineering Drawing #2 of the Boundary Condition Box

Table 3-3: List of Boundary Condition Box Specifications

Physical Description:

The Boundary Condition Box Support Structure is made from 2 sets of 2 identical 6061 Aluminum pieces. When these pieces are put together, they form a rectangular box: 6.55 inches square outside with wall thickness 1.00 inch, 4.55 inches square inside, and 25.00 inches in length. These pieces are held together by removable screws for ease of assembly/disassembly. The 6.55 inch wide piece has eight (8) screw holes and the 4.55 inch wide piece has eight (8) screw taps. Sixteen (16) 1.75 inch long screws structurally hold the pieces into the box form. In addition to the assembly screw holes and taps, each piece has four (4) 0.50 inch screw taps for attachment of strip heaters.

Specifications:

Material		6061 Aluminum
Piece No. 1	Quantity	2
	Width	6.55 inches ± 0.01
	Length	25.00 inches ± 0.05
	Thickness	1.00 inch ± 0.01
	Locations:	
	Screw holes	specified distance (inches) ± 0.01
	Screw taps	specified distance (inches) ± 0.01
Piece No. 2	Quantity	2
	Width	4.55 inches ± 0.01
	Length	25.00 inches ± 0.05
	Thickness	1.00 inch ± 0.01
	Locations:	
	Screw holes	specified distance (inches) ± 0.01
	Screw taps	specified distance (inches) ± 0.01

The material, aluminum 6061, and the wall thickness, 1.00 inch, of the Boundary Condition Box Support Structure were chosen to ensure that the interior box wall provided a nearly isothermal boundary.

The second component of the Boundary Condition Box is the heaters attached to the box. Three types of are heaters used: strip heaters, flexible heaters, and ribbon heaters. Each heater type is discussed individually.

The strip heaters are stock order Mica Strip Heaters supplied by Watlow Electric Manufacturing Company in St. Louis, Missouri. The Watlow stock number is S1J23NU3. The strip heaters are 23.75 inch long, 1.5 inch wide stainless steel sheathed heaters with a 21 inch long heated region with precut mounting holes. Each strip heater is rated for 120 Volt/750 Watts with a maximum power density of 24 Watts per square inch [W-2]. Two strip heaters are attached to each support structure side for a total of eight strip heaters. They are electrically configured with 4 parallel sets of 2 heaters in series as shown in Figure 3-7. Two additional heaters are available for backup use if necessary.

The flexible heater is a stock order Silicone Rubber Rectangle (Etched-Foil Construction) supplied by Watlow Electric Manufacturing Company in St. Louis, Missouri. The Watlow stock number is F060050C7. The silicone heater is a 5 inch long, 6 inch wide heater with an etched-foil resistance element vulcanized between two thin layers of fiberglass-reinforced silicone rubber; it is approximately 0.018 inch thick. The

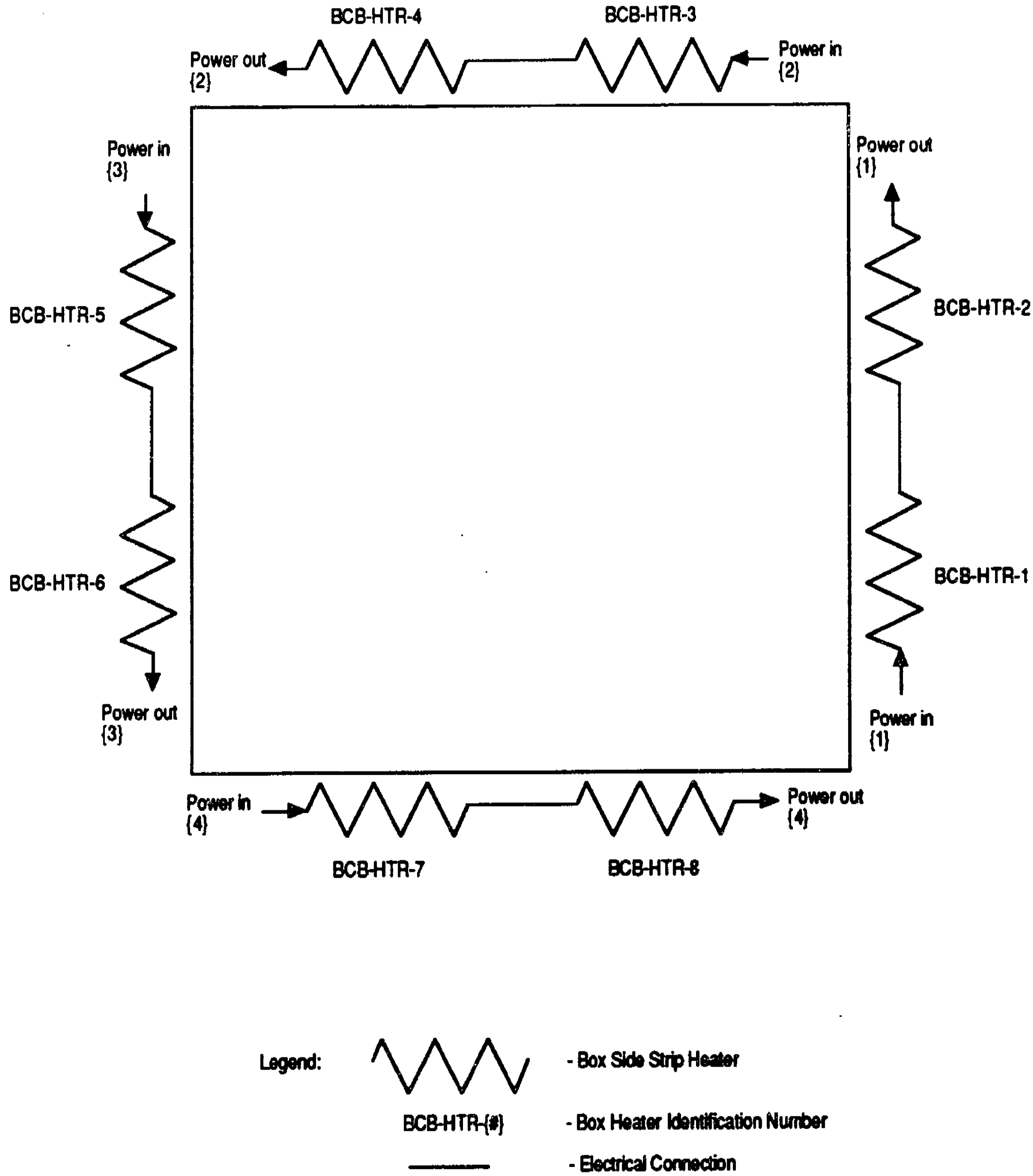

Figure 3-7: Electrical Configuration of the Boundary Condition Box Strip Heaters in the Experimental Apparatus

silicone heater is rated at 120 Volts/300 Watts with a maximum power density of 10 Watts per square inch [W-2]. This heater is attached to the non-lead end of the support structure with RTV106 Silicone Sealant manufactured by General Electric Company. One spare heater is available for use if necessary.

Due to potential outgassing problem with the silicone rubber heater at extremely low pressures, an additional type of flexible heater was purchased. This other flexible heater is a stock order Kapton® Heater supplied by Watlow Electric Manufacturing Company in St. Louis, Missouri. The Watlow stock number is K050050C3. The Kapton® Heater is a 5 inch long, 5 inch wide heater with an etched-foil resistance element in a Kapton® film which is coated on one side with a layer of FEP teflon; it is approximately 0.007 inch thick. The Kapton® Heater is rated at 120 Volts/125 Watts with a maximum power density of 5 Watts per square inch [W-2]. This heater type was not used on this experimental apparatus since testing was not performed at extremely low pressures. Two heaters are available for use if necessary.

The ribbon heater is a stock order Heavy Insulated Ultra-High Temperature Heating Tape supplied by Omega Engineering Incorporated in Stamford, Connecticut. The Omega stock number is STH051-060. The heating tape is a 6 feet long, 0.5 inch wide ribbon heater with fine gage (36-40) stranded resistance wires surrounded with Samox® braiding insulation. It is rated at 120 Volts/470 Watts with a maximum power density of 13 Watts per square inch [O-1]. The heating tape is wound between the lead end of the Heater Rods in the configuration shown in Figure 3-8. One spare heater is available for use if necessary.

The Boundary Condition Box provides the boundary conditions for the experimental apparatus and supports the Heater Rod array arranged by the Rod Support Plates. The Box is centered in the Containment Vessel. The Containment Vessel is discussed in Section 3.5.

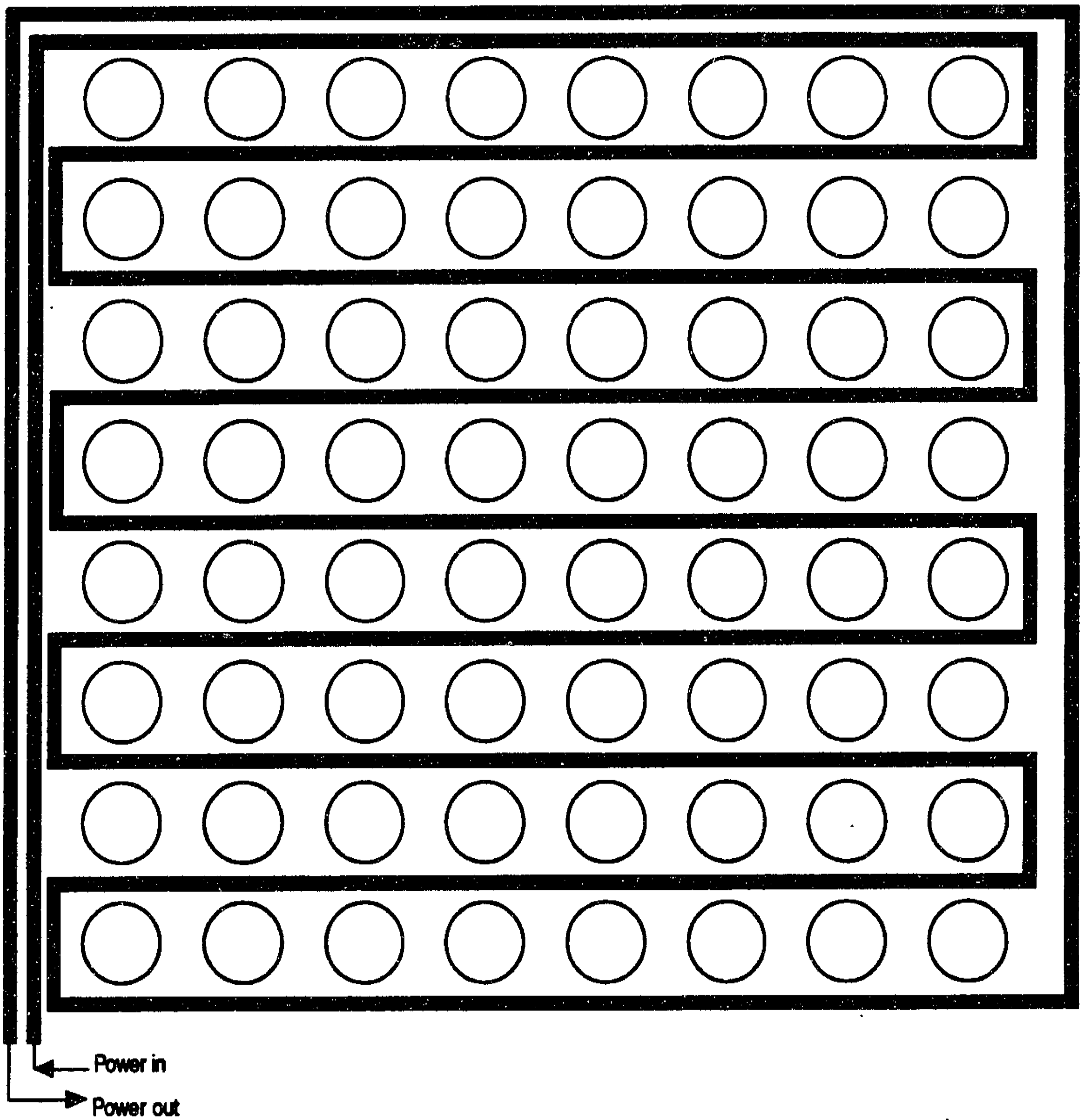

Figure 3-8: Winding Configuration of the Non-lead End Ribbon Heater

3.5 CONTAINMENT VESSEL

The Containment Vessel (CV-VS-1) is a special order pressure/vacuum vessel fabricated by Massachusetts Engineering Company in Avon, Massachusetts. The manufacturer's drawing of the Containment Vessel and Form U-1A "Manufacturer's Data Report for Pressure Vessels" are provided in Figures 3-9 and 3-10, respectively; and a list of the Containment Vessel's specifications is provided in Table 3-4.

The Containment Vessel is an ASME approved and stamped pressure (75 psig)/full vacuum vessel constructed from 18 inch outside-diameter, 62 inch long SA53-B Carbon Steel pipe with a 0.375 inch wall thickness sealed at each end with 150 pound SA105 Carbon Steel flanges. The Containment Vessel ends are sealed with a standard 18.25 inch inside diameter gasket between the flanges. The vessel has a total of 13-3/4 inch female NPT threaded tap penetrations at locations shown in Figure 3-9. Additional features provided on the vessel are lift lugs on each blank flange and on the vessel itself for lifting the vessel and two 6 inch high cradles to support the vessel weight of 900 pounds.

Nine of the thirteen penetrations are utilized in the experiment. One penetration is used for the dual pressure safety relief valves; one penetration is used for the compound pressure gauge; one penetration is used for power feedthroughs; five penetrations are used for thermocouple feedthroughs; one penetration is used for the

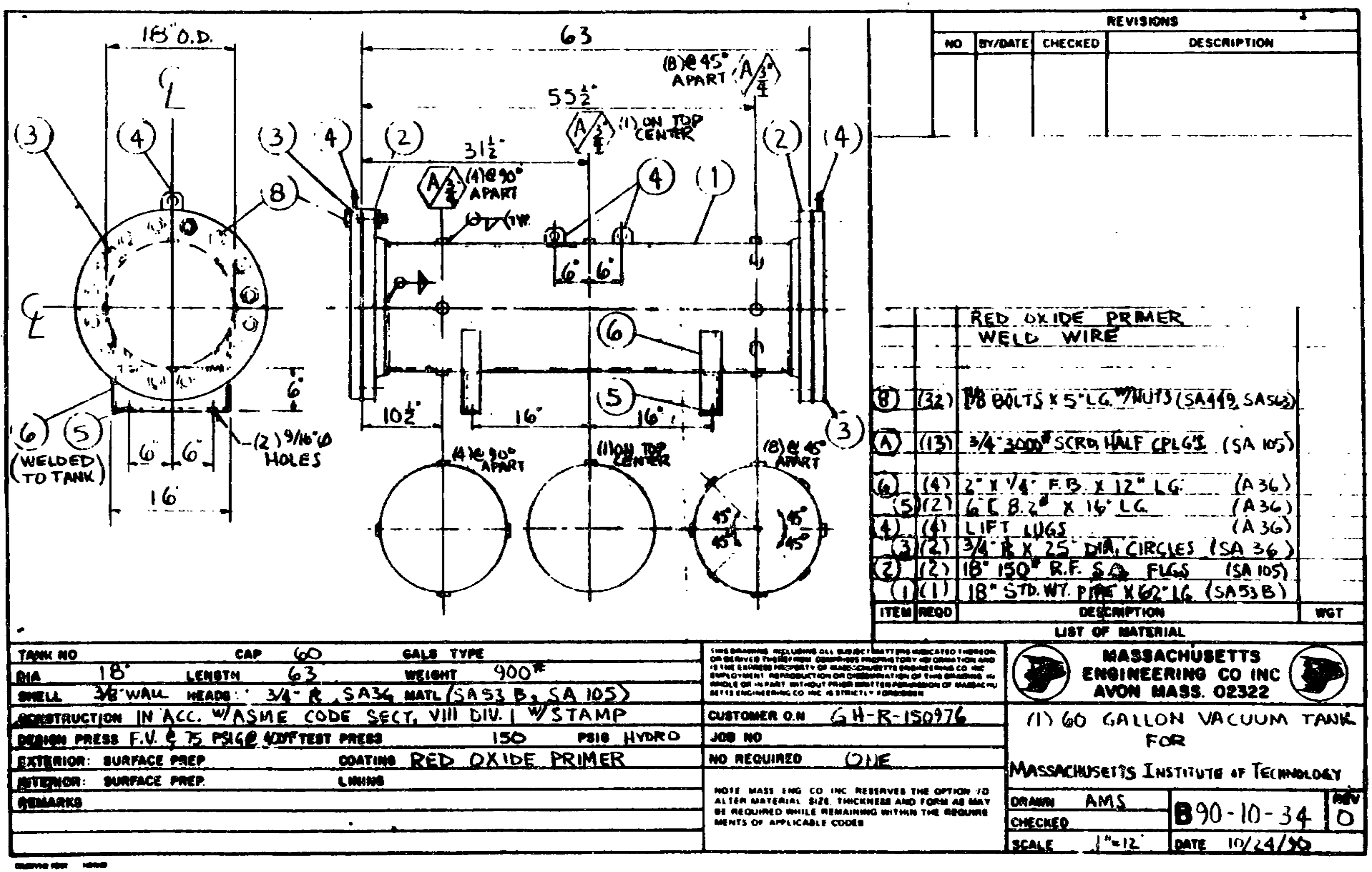

Figure 3-9: Engineering Drawing of the Containment Vessel

FORM U-1A MANUFACTURER'S DATA REPORT FOR PRESSURE VESSELS
(Alternative Form for Single Chamber, Completely Shop-Fabricated Vessels Only)

As Required by the Provisions of the ASME Code Rules, Section VIII, Division 1

1. Manufactured and certified by Massachusetts Engineering Co., Inc., 40 Murphy Drive, Avon Industrial Park, Avon, MA 02322

2. Manufactured for Massachusetts Institute of Technology, Cambridge, MA

3. Location of installation Cambridge, MA 02139

4. Type Horizontal | 89156 | -- | 890-10-34 Rev.0 | 5759 | 1990

5. The chemical and physical properties of all parts meet the requirements of material specifications of the ASME BOILER AND PRESSURE VESSEL CODE. The design, construction, and workmanship conform to ASME Rules, Section VIII, Division 1 1989 to A89 | -- | --

6. Shell: SA53-B | 0.375 | -- | 1'-6" O.D. | 5'-2"

7. Seams: Welded pipe | -- | 85 | -- | -- | Double lap | -- | 1

8. Heads: (a) Matl. SA105 (b) Matl. --

	Location (Top, Bottom, Ends)	Minimum Thickness	Corrosion Allowance	Crown Radius	Knuckle Radius	Elliptical Ratio	Conical Apex Angle	Hemispherical Radius	Flat Diameter	Side to Pressure (Convex or Concave)
(a)	Ends	150#	--	--	--	--	--	--	32"	Flat
(b)										

If removable, bolts used (describe other fastenings) (32) 1-1/8" dia. SA449 bolts with SA563 nuts

9. MAWP F.V. + 75 psi at max. temp. 400 °F
*Min. design metal temp. 0 °F at 75 psi. Hydro., pneu., or comb. test pressure 150 psi.

10. Nozzles, inspection and safety valve openings: Elsewhere in system**

Purpose (Inlet, Outlet, Drain)	No.	Diam. or Size	Type	Matl.	Nom. Thk.	Reinforcement Matl.	How Attached	Location
--	13	3/4"	cplg.	SA105	3000#	--	Welded	Shell

11. Supports: Skirt No Lugs 0 Legs 0 Other (2) 6" brackets Attached Shell - welded

12. Remarks: Manufacturer's Partial Data Reports properly identified and signed by Commissioned Inspectors have been furnished for the following items of the report: --

*Impact testing not req'd./UG20(F). 60 gal. vacuum tank. OAL - 5'-3"
No. of lifting lugs on tank - two. P.O.No. GH-R-150976
**User must provide overpressure protection before testing or using vessel.

CERTIFICATE OF SHOP COMPLIANCE

We certify that the statements made in this report are correct and that all details of design, material, construction, and workmanship of this vessel conform to the ASME Code for Pressure Vessels, Section VIII, Division 1. "U" Certificate of Authorization No. 162 expires 8/28, 1993.
Date 11/30/90 Co. name Mass. Engr. Co.,Inc. Signed [signature]

CERTIFICATE OF SHOP INSPECTION

Vessel constructed by Massachusetts Engineering Co.,Inc. at Avon, MA 02322.
I, the undersigned, holding a valid commission issued by the National Board of Boiler and Pressure Vessel Inspectors and/or the State or Province of Massachusetts and employed by Arkwright Mutual Ins. Co., Norwood, MA*** have inspected the component described in this Manufacturer's Data Report on 11-30, 1990, and state that, to the best of my knowledge and belief, the Manufacturer has constructed this pressure vessel in accordance with ASME Code, Section VIII, Division 1. By signing this certificate neither the Inspector nor his employer makes any warranty, expressed or implied, concerning the pressure vessel described in this Manufacturer's Data Report. Furthermore, neither the Inspector nor his employer shall be liable in any manner for any personal injury or property damage or a loss of any kind arising from or connected with this inspection.
***Factory Mutual System
Date 11-30-90 Signed [signature] Commissions NB-8446, Mass.1287

(12/87) This Form (E00117) may be obtained from the ASME Order Dept., 22 Law Drive, Box 2300, Fairfield, NJ 07007-2300

Figure 3-10: Containment Vessel's Form U-1A "Manufacturer's Data Report for Pressure Vessels"

Table 3-4: List of Containment Vessel Specifications

Physical Description:

ASME Code approved and stamped pressure-vacuum vessel constructed from 18 inch (outside diameter) pipe that is 5 feet long with bolted and blind flanges at each end. The vessel has a total of 13 3/4 inch female NPT threaded tap penetrations.

Specifications:

Material (pipe)	SA 53B Carbon Steel
Length (pipe w/o flanges)	60 inches ± 1
Outside Diameter	18 inches ± 0.1
Penetrations	Total of 13 3/4 inch female NPT threaded taps Locations: A. 9 inches ± 0.25 from end of pipe Number: 4 radially spaced 90 degrees ± 2 starting from the top of the vessel B. 30 inches ± 0.25 from end of pipe Number: 1 at the top of the vessel C. 54 inches ± 0.25 from end of pipe Number: 8 radially spaced 45 degrees ± 2 starting from the top of the vessel
Design Pressures	Minimum: Full Vacuum Maximum: 75 psig ± 1
Design Temperature	200 degrees C ± 5
Design Fill Gases	N_2, He, Ar, SF_6, CO_2

Containment Vessel Pressure System; and one penetration is used for the Containment Vessel Vacuum System. Figure 3-11 shows the Containment Vessel System.

The dual pressure safety relief valves are Anderson Greenwood Type 83 Safety Relief Valves supplied by Piping Specialties in Needham, Massachusetts. The manufacturer's part number is 83S46-4L. The valves have a Kalrez® perfluoroelastomer O-Ring seat for its severe heat and chemical resistant properties. The valve body and trim are 316 Stainless Steel with 1/2 inch female inlet, 3/4 inch female outlet, and a packed lift lever [A-2]. One valve (CV-PRV-1), serial number 90-22437, has a set lift pressure of 20 psig and blowdown capacity of 28 standard cubic feet per minute air; the other valve (CV-PRV-2), serial number 90-22438, has a set lift pressure of 24 psig and a blowdown capacity of 31 standard cubic feet per minute air. These valves are directly installed on the Containment Vessel with a threaded Tee-fitting.

The gauge (CV-PG-1) is a Marshalltown Compound Pressure and Vacuum Gauge supplied by McMaster Carr Supply Company in Dayton, New Jersey. The supplier's part number is 4004K35. The gauge is a phosphor bronze bourdon tube (ANSI Grade B - 2% Accuracy) with a 4.5 inch dial indicating 150 psig to 30 inches Hg total graduations [M-5]. The gauge is installed directly in one of the top vessel penetrations.

The power feedthrough and the thermocouple feedthroughs were fabricated in-house for budget/economics reasons. Due to safety and legal (State of Massachusetts)

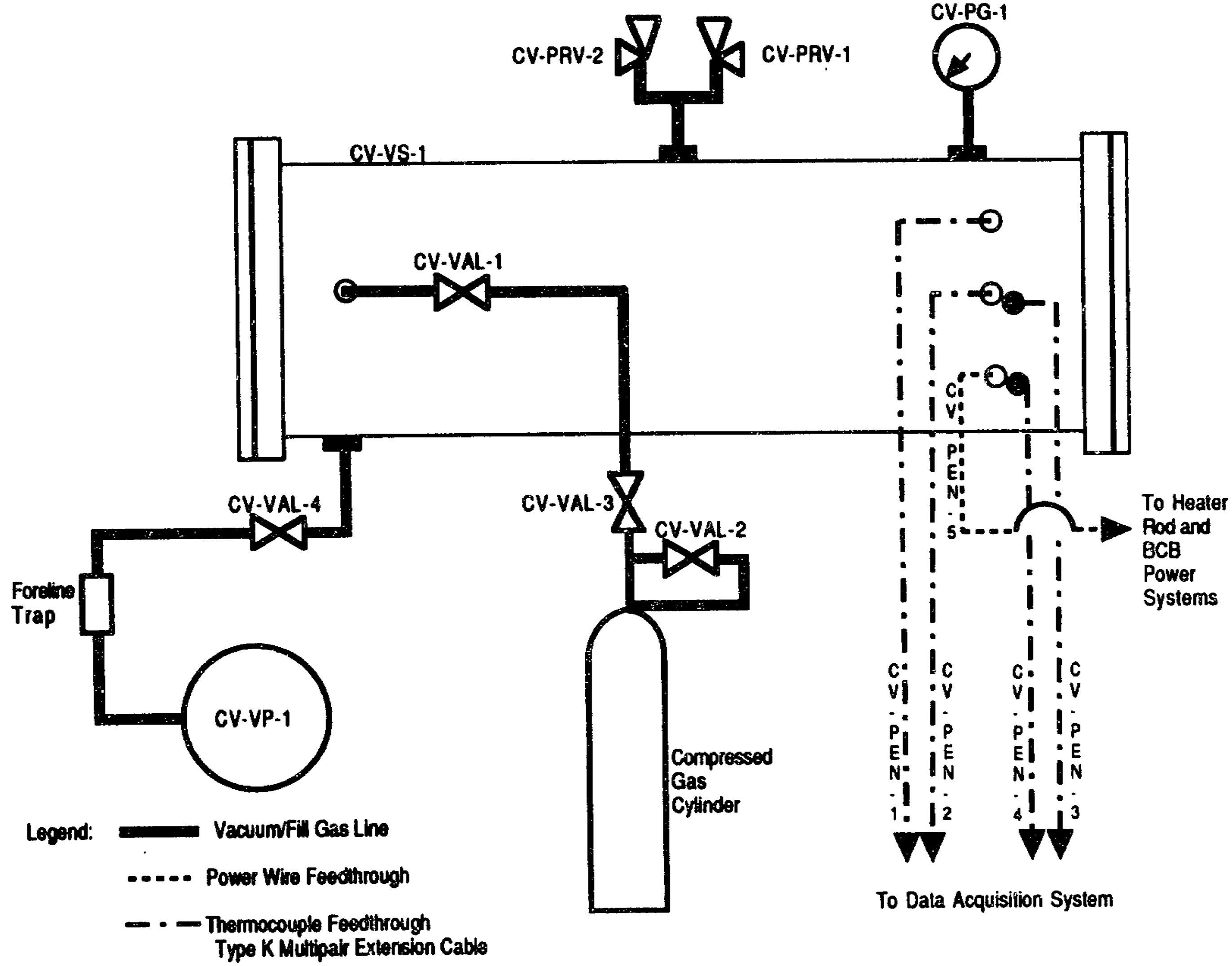

Figure 3-11: System Drawing - Containment Vessel

concerns, these in-house fabricated feedthroughs limited pressure operation of the vessel to no higher that 20 psig.

The power feedthrough and the thermocouple feedthroughs were fabricated from compression fittings, epoxy, and solid strand wire. The power feedthrough wire is THHN Premium Building Wire supplied by McMaster-Carr Supply Company in Dayton, New Jersey. The supplier's part numbers are 7125K72 (color: black) and 7125K82 (color: white). The power wire is 12 AWG solid copper conductor with PVC insulation (UL 83 and 1063) rated for 600 Volts [M-5]. The black and white wires are paired as power in and power out respectively. There are 12 pairs of power wires in the power feedthrough. The thermocouple feedthrough wire is Multipair Thermocouple Extension Cable supplied by Omega Engineering Incorporated in Stamford, Connecticut. The supplier's catalog number is 20KX20PP. The thermocouple cable is 20 AWG type K (Chromel, (+) lead; and Alumel, (-) lead) with 20 twisted and marked pairs [O-2]. The thermocouple feedthroughs each have 30 thermocouple pairs.

The power feedthrough and the thermocouple feedthroughs were assembled identically. Each feedthrough wire is held together with a 3/4 inch NPT Thermo Electric steel compression fitting centered on 2 feet of wire. The fitting has a rubber bushing that compressed around the feedthrough wire as the fitting was tightened [T-1]. To ensure an air tight feedthrough, Devcon® epoxy adhesive was applied between the wires in the compression fitting and to the end of each feedthrough wire.

The Containment Vessel Pressure System is the system used to pressurize the Containment Vessel with the desired heat transfer medium. The Pressure System consists of a compressed gas cylinder, an isolation valve (CV-VAL-3) and a regulator valve (CV-VAL-2) for the compressed gas cylinder, and an isolation valve (CV-VAL-1) between the vessel and the compressed gas cylinder regulator valve. The gas cylinders with the desired heat transfer medium are stock order AIRCO products supplied by MIT Laboratory Supplies in Cambridge, Massachusetts. The MIT stock numbers are 340090, 340000, and 330020 for Nitrogen, Helium, and Argon, respectively. Table 3-5 lists the purity specifications for each heat transfer medium. The Containment Vessel Pressure System Operating Process is discussed in Section 4.3. After operation with one heat transfer medium is completed, its compressed gas cylinder is removed from the system and replaced with the next desired heat transfer medium's compressed gas cylinder.

The Containment Vessel Vacuum System is used to operate the experimental apparatus at below atmospheric pressure. The Vacuum System consists of a vacuum pump (CV-VP-1) and an isolation valve (CV-VAL-4) between the vessel and the vacuum pump. The vacuum pump is a Sargent-Welch Scientific Company Model 1405 belt-driven two-stage vacuum pump. The vacuum pump in-take line has an MDC Vacuum Products Corporation Model KTX-075-2 Foreline Trap installed. The foreline trap prevents backstreaming of hydrocarbons. These vacuum components are on loan from another research project at MIT. The Containment Vessel Vacuum System Operating Process is discussed in Section 4.3.

Table 3-5: Heat Transfer Medium Purity Specifications [E-1]

Heat Transfer Medium	Purity	Oxygen Content	Moisture Content
Pre-Purified Nitrogen	99.995%	< 5 ppm	< 10 ppm
Commercial Grade Helium	99.995%	< 10 ppm	< 15 ppm
Commercial Grade Argon	99.997%	< 5 ppm	< 10.5 ppm

The Containment Vessel System was operated and observed to determine appropriate leakage rates. In the above atmospheric pressure operating range with Helium as the heat transfer medium, the vessel was observed to leak 5 psi in approximately 9 hours starting at a pressure of 20 psig. In the below atmospheric pressure operating range, the vessel's observed inleakage was 1 inch Hg in approximately 28 hours starting at a pressure of 26 inches Hg.

3.6 INSTRUMENTATION AND CONTROL

The experiment's instrumentation can be broken down into two types of Instrumentation and Control Systems. These systems are: the Data Acquisition System and the Power Systems. Each system type is discussed individually in this section.

As directed by MIT NED Administrative Procedure 2.8, "Control of Measuring and Test Equipment," instruments used for support of data gathering activities "shall be calibrated utilizing reference standards whose calibration is certified as being traceable to the National Institute of Standards and Technology (NIST)" [M-3]. A copy of MIT NED AP 2.8 is provided in Appendix A. Each instrument used on this research project has a current calibration to NIST standards.

The Data Acquisition System in comprised of Hewlett Packard components on loan from several research projects at MIT. The Data Acquisition System consists of a data acquisition/control unit (DAU-DAU-1) with 5 multiplexer cards (DAU-M-1 through 5) and an integrating voltmeter (DAU-V-1) installed, a computer with a central processing unit (DAU-COM-1) and a data storage unit (DAU-COM-2), and a printer (DAU-PRT-1). Figure 3-12 shows the Data Acquisition System.

The data acquisition/control unit is a Hewlett Packard Model 3852A. This unit has the ability to support 8 plug-in function modules. The plug-in function modules used

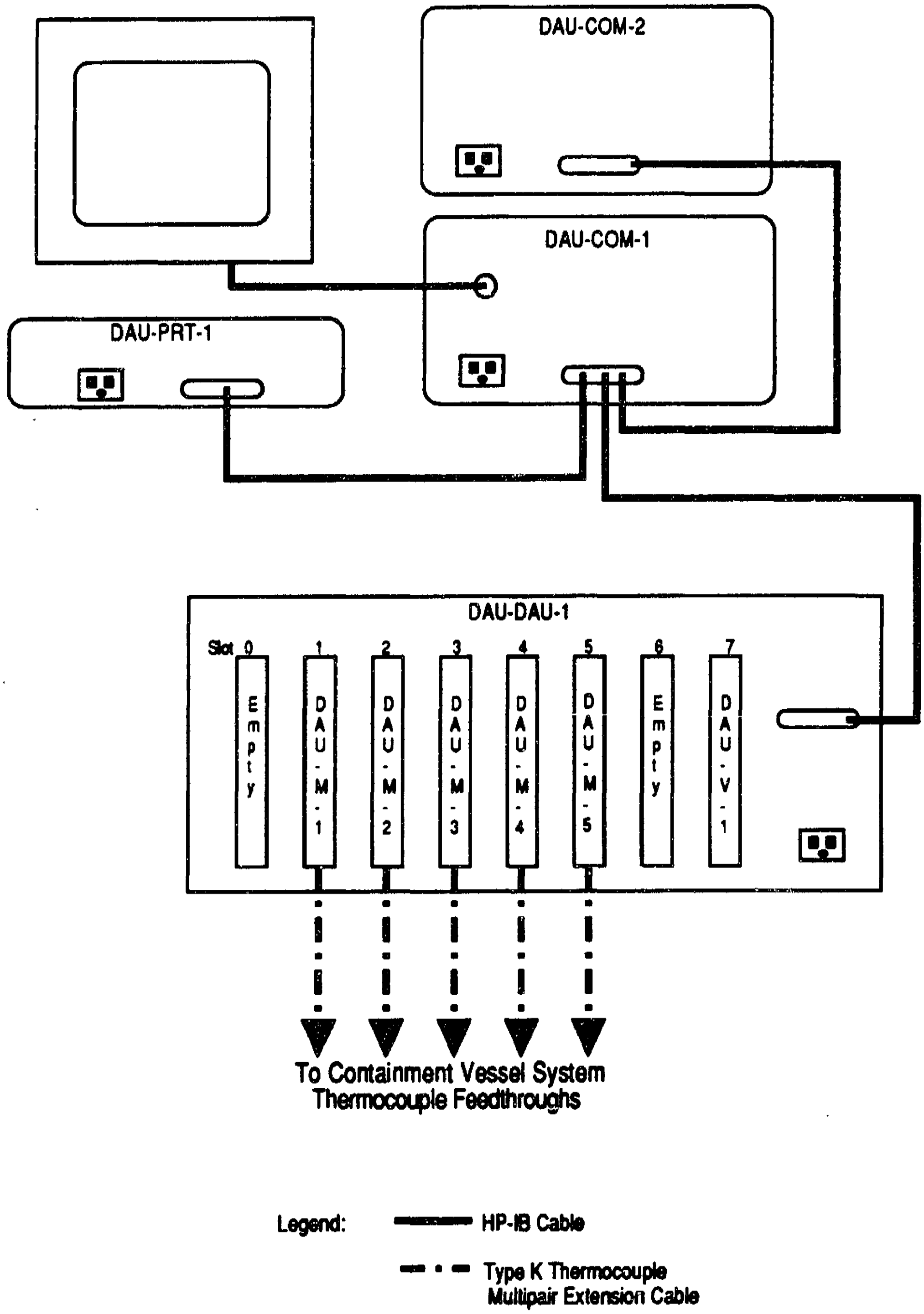

Figure 3-12: System Drawing - Data Acquisition System

are five Hewlett Packard Model 44708A modules, 20 Channel Relay Multiplexers, and one Hewlett Packard Model 44701A module, a 5 1/2 digit Integrating Voltmeter. These modules were chosen due to their ability to reject common-mode noise. Additionally, the relay multiplexers automatically handle thermocouple compensation [H-1]. As advised by Hewlett Packard through General Electric Company in a letter from Mr. Robert S. Sellon to the author dated March 1, 1991, Hewlett Packard Model 44708A relay modules do not require calibration since they "are relays and have no effect on the system's accuracy" [S-7]. A copy of this letter is provided in Appendix B. Both the data acquisition/control unit and the integrating voltmeter have current calibration to NIST standards.

The computer used in the Data Acquisition System is a Hewlett Packard 9000/300 Series Model 9153A with a 10 Megabyte hard drive and a 3 1/2 inch floppy drive. The printer is a Hewlett Packard ThinkJet Model 2225A.

The thermocouple wire used to connect the penetrations to the multiplexers is Multipair Thermocouple Extension Cable supplied by Omega Engineering Incorporated. The thermocouple cable is 20 AWG type K (Chromel, (+) lead; and Alumel, (-) lead) with 20 twisted and marked pairs [O-2].

The experimental apparatus has two separate control systems for power. The first is the Heater Rod System; the second is the Boundary Condition Box System. Each of these systems are discussed in this section. Figures 3-13 and 3-14 show the Heater Rod System and the Boundary Condition Box System, respectively. To limit the voltage input to each system, variable transformers were placed between the power supplies and the control units. These variable transformers are used to limit the thermal stresses to the Heater Rods in the Heater Rod System and to limit the power to the Boundary Condition Box heaters so that their power ratings are not exceeded. The variable transformers are on loan from other research projects at MIT.

The Heater Rod System controls and monitors the power delivered to the Heater Rods. Electronic Control Systems (ECS) Control/Alarm Model 6400-K-4-1-1-2-1 is the unit that controls the power delivered to the Heater Rods. The unit's Control Module, ECS Model 6414, (ROD-C-1) provides the control function. It controls the power by controlling the temperature of the Heater Rod in Position 4-4. The unit's Alarm Module, ECS Model 6460, (ROD-ALA-1) is a safety feature. It monitors the temperature of the Heater Rod in Position 5-5 and will disconnect power to the Heater Rods if its setpoint is exceeded. During operation, the alarm setpoint is set 10° higher than the control setpoint.

Redundant instrumentation for current, voltage, and power are provided in the Heater Rod System to monitor the power delivered to the Heater Rods. Each function is monitored with an analog instrument and a digital instrument. Current is monitored with a Simpson Model 59 Analog AC Ammeter (ROD-A-2) and a Simpson Model 2869

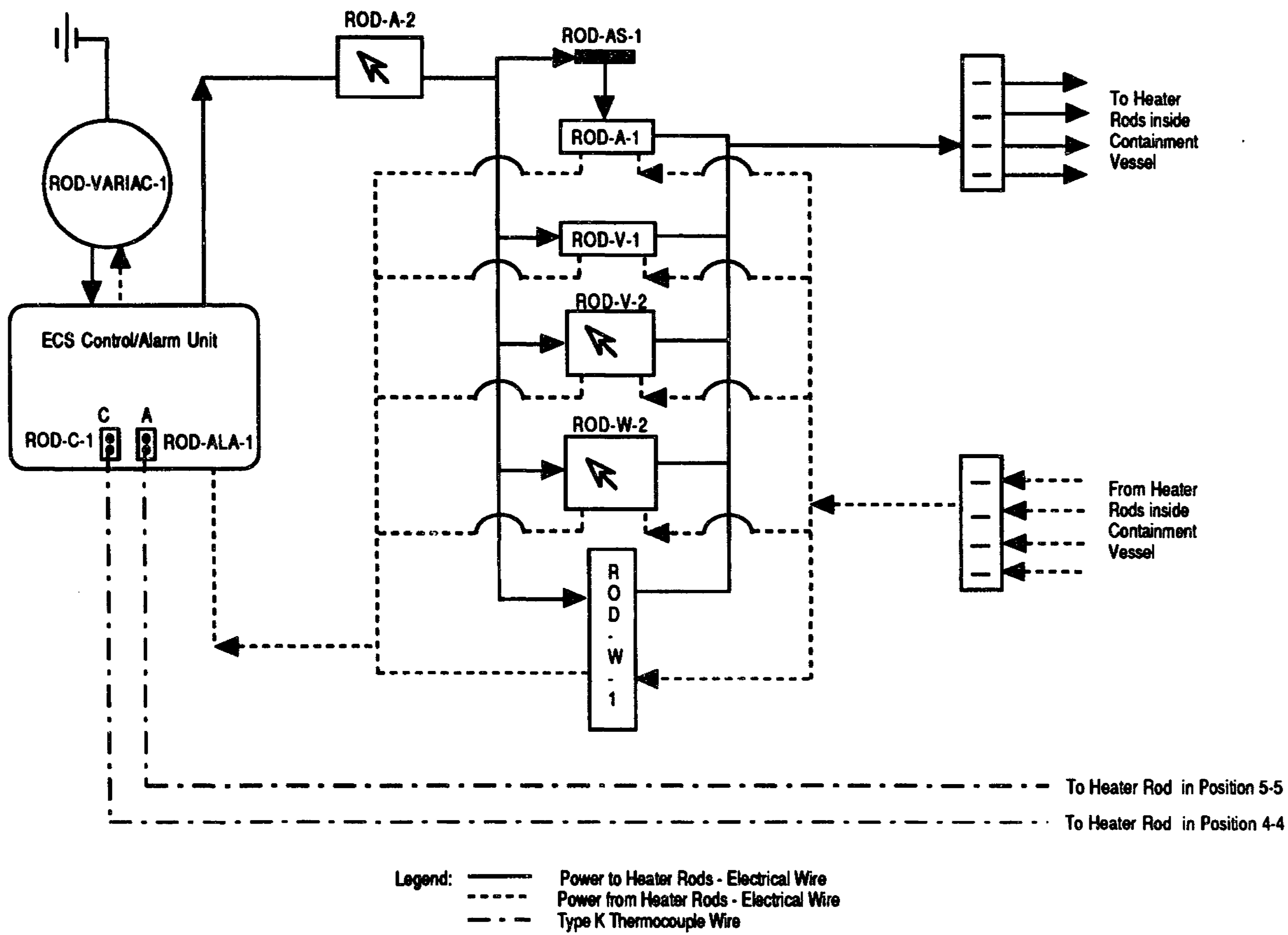

Figure 3-13: System Drawing - Heater Rod System

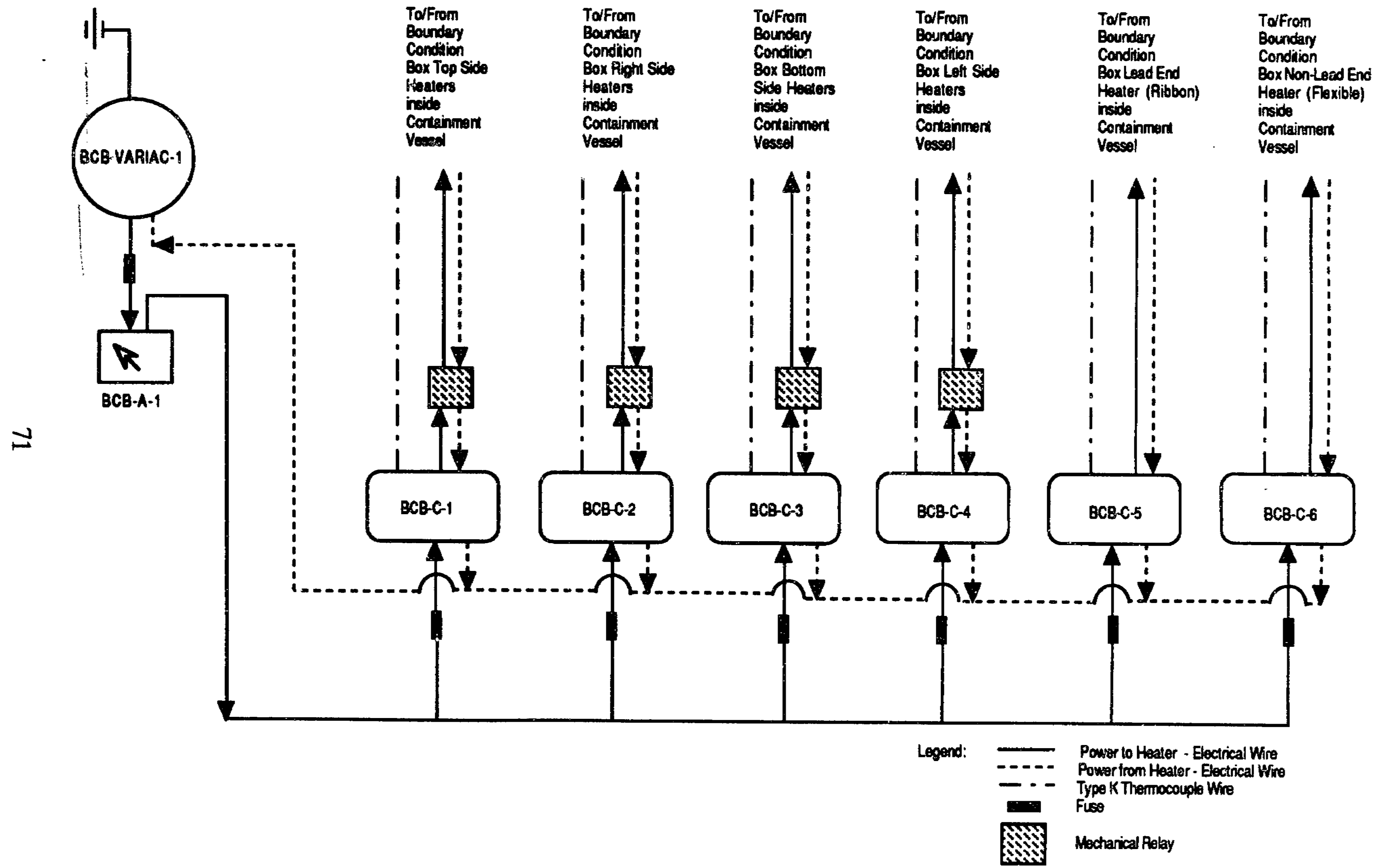

Figure 3-14: System Drawing - Boundary Condition Box System

Digital AC Millivolt Meter (ROD-A-1) with a General Electric Model EM/HA-10-100 (10 amp:100 millivolt) Shunt (ROD-AS-1). Voltage is monitored with a Simpson Analog Voltmeter (ROD-V-2), a Newport Model 201AN-AC6 Digital AC Voltmeter (ROD-V-1), and a Hewlett Packard Model E2377A Multimeter selected to the AC Voltage function (ROD-V-3). Power is monitored with a Simpson Model 79 Analog Wattmeter (ROD-W-2) and an ECS Model 6558-1-2-4-3-2-0-0-0 Watts Transducer (ROD-W-1) with an installed General Electric Type JA1-0 Current Transformer (ROD-CT-1) calibrated with 5 primary turns. Each instrument was purchased from an approved vendor and has current calibration to NIST standards. A list of approved vendors is provided in Appendix B.

The instruments were electrically connected with insulated 14 AWG braided copper wire with fuses installed in-line to protect the instrumentation from power spikes.

The Boundary Condition Box System controls the power delivered to each box side and end. Each box side and end has its own controller. Omega Model CN9111 Microprocessors (BCB-C-1, BCB-C-2, BCB-C-3, and BCB-4) control the power delivered to the box sides heaters (top, right, bottom, and left sides, respectively), and Omega Model CN9111A Microprocessors (BCB-C-5 and BCB-C-6) control the power delivered to the box ends heaters (lead and non-lead ends, respectively). These microprocessors control the power to the box sides by controlling the temperature of centrally attached thermocouples and to the box ends by controlling the temperature of the thermocouple attached to the end of the Heater Rod in Position 2-7. The box sides microprocessors function as on/off controllers due to installed Omega Model MC1-2-30-120 Mechanical Relays in each power line to prevent excessive cycling of the microprocessors. Additionally, fuses have been installed to prevent a power spike from affecting the instrumentation. As mentioned earlier, the voltage is limited by a variable transformer (BCB-VARIAC-1). The current is monitored with a Simpson Model 59 Analog AC Ammeter (BCB-A-1). Each instrument was purchased from an approved vendor and calibrated to NIST standards. A list of approved vendors is provided in Appendix B. The instruments were electrically connected with insulated 14 AWG braided copper wire.

3.7 ASSEMBLY OF EXPERIMENTAL SYSTEM

This section describes the assembly of the experimental system. It provides detail on how the equipment is assembled and other details that should be noted.

Prior to assembly of the experimental system, the Heater Rods were inspected as discussed in Section 3.2. After inspection, the Heater Rods, Rod Support Plates, and the interior walls of the Boundary Condition Box were painted black. These components were painted so that their emissivity could be approximated at 0.9. The paint used for this purpose was black Krylon High Heat Spray Paint. The paint withstands temperatures up to 315°C for long periods of time without deteriorating, and dries within 5 minutes to prevent runs and drips.

After painting the items, the assembly of the experimental system began. Eight Heater Rods were placed in the Rod Support Plates one row at a time. After each rod was inserted in the Rod Support Plates, the rod was electrically connected to its nearest neighbor with VOLTREX® Non-insulated High-Temperature Butt Connectors. After each rod was connected, continuity was checked using a multimeter to ensure that the power wires were connected to the Heater Rod and that there was no short between the Heater Rods and the Rod Support Plates. After a row of 8 Heater Rods was installed and connected, the non-insulated connectors were coated with a mixture of Sauereisen Electric Heater Cement (No. 6 Powder) and water. The cement coated connectors were dried with heated air from a forced heating unit. The Heater Rods were electrically connected in 4 sets of 16 Heater Rods connected in series. Figure 3-2 shows the electrical configuration of the Heater Rods, and Figure 3-3 shows the arrangement of the Heater Rods in the 8x8 array by their unique identifying numbers assigned during the Heater Rod Inspection.

The Heater Rods, now supported in a square array by the Rod Support Plates, were then placed in the Boundary Condition Box. The box had already been assembled with Mica Strip Heaters and the Ribbon Heater as described in Section 3.4. To ensure the equipment would work, the Heater Rods and Boundary Condition Box side heaters were electrically connected for testing to their respective Instrumentation and Control components described in Section 3.6 and illustrated in Figures 3-13 and 3-14, respectively. The box side heaters were operated with temporary thermocouples attached to the surface of each box side. The equipment performed as expected and was ready to be placed inside the Containment Vessel.

A support stand was fabricated to center the Boundary Condition Box inside the Containment Vessel. The support stand was designed to have minimal contact with the box. The stand was fabricated out of bolted DEXION metal strips coated with a mixture of Sauereisen Electric Heater Cement (No. 6 Powder) and water, at the points were the stand would contact the Boundary Condition Box. The cement was used to prevent a potential short circuit path from the electrically heated components to the Containment

Vessel and to minimize the heat conducted from the box to the support stand and to the Containment Vessel. The support stand was placed inside the Containment Vessel above the Containment Vessel Vacuum System penetration (see Figure 3-11).

After the support stand was situated in the Containment Vessel, the Boundary Condition Box was placed horizontally inside the Containment Vessel on the support stand. A Starrett No. 130 Precision Iron Bench Level was used to ensure that the box was horizontally level inside the Containment Vessel.

The penetration components discussed in Section 3.5 were then installed on the Containment Vessel. The power wires of the Heater Rods and the Boundary Condition Box side heaters were attached to the power feedthroughs with non-insulated butt connectors and insulated with high temperature electrical tape. As each wire was attached to a feedthrough wire, a label was attached to the exterior penetration wire identifying the wire path. The thermocouple wires of the Heater Rods were then attached to the thermocouple feedthroughs. As each Heater Rod thermocouple was attached to the interior penetration, the Heater Rod identifying label was removed from that thermocouple and placed on the exterior penetration. The electrical continuity of these connections were continually checked and verified with the multimeter's continuity function. During the continuity check, the thermocouple of the Heater Rod in Position 3-2 (Rod ID No. G-8) was discovered to have an open circuit. Therefore, this position does not have a functioning thermocouple. The exterior power penetration feedthrough wires and the controlling thermocouple were then attached to the Heater Rod System and the Boundary Condition Box System (see Figures 3-13 and 3-14, respectively).

After the Heater Rod thermocouples were attached to the thermocouple feedthroughs, thermocouples were installed on the Boundary Condition Box surface and the ends of 5 Heater Rods. Four type K thermocouples were attached to the surface of each box side with high temperature and high thermally conductive epoxy; one positioned 2 inches, two positioned 12.5 inches, and one positioned 23 inches from the end of the box. One type K thermocouple was attached to the end of each Heater Rod in the following positions (with the same type of epoxy): Position 1-1, Position 2-7, Position 4-4, Position 5-5, and Position 7-3. The epoxy used is OMEGABOND® 200 which is recommended for accuracy to 260°C for beaded wire thermocouples. The epoxy cures at elevated temperatures: 8 hours at 120°C or 2 hours at 200°C [O-2]. Both the Heater Rods and the Boundary Condition Box side heaters were operated to cure the thermocouple epoxy. This curing process also provided proof that the experimental apparatus was operational.

It is noted at this point that during the Debugging Phase, discussed in Section 4.5, the epoxied thermocouples were determined not to provide an accurate measurement of the actual wall temperature. To rectify this, thermocouples were mechanically attached to the Boundary Condition Box sides. This problem and its solution are discussed in Section 4.5.

After the thermocouples had properly cured, the Boundary Condition Box non-lead end flexible heater, Silicone Rubber Rectangle, was attached to the 1 inch thick box support structure with RTV106 Silicone Sealant. This sealant cured at room temperature in approximately 8 hours.

The epoxied thermocouples and the Containment Vessel environment thermocouples (one located at the box end of the vessel and one located at the wire end of the vessel) were then attached to the thermocouple feedthrough. The identifying label for each thermocouple was transferred to the appropriate exterior penetration wire. At this time, all of the thermocouples were attached to the feedthroughs.

The final major step was to attach the exterior thermocouple feedthrough penetration wires to the Data Acquisition Systems' multiplexer modules. This step was accomplished with hours of care and caution to ensure that each thermocouple connected was assigned the appropriate multiplexer channel number.

After completing the thermocouple attachment to the Data Acquisition System and verifying that the Containment Vessel internals were connected and cured, the Containment Vessel ends were sealed. The experimental apparatus was now ready for testing, beginning with the Debugging Phase discussed in Section 4.5.

3.8 CHAPTER SUMMARY

Chapter 3 describes the design and construction of the experimental apparatus. The major components of the experiment are:

(1) the Heater Rods;

(2) the Rod Support Plates;

(3) the Boundary Condition Box;

(4) the Containment Vessel; and

(5) the Instrumentation and Control Equipment.

The design and construction of each major component is discussed in detail. In addition, each item in the experimental apparatus is identified by a unique identification label by the item's system, function and a sequential number of similar items in the system as required by the Quality Assurance Program discussed in Chapter 2. Important points to note from the assembly of the experimental apparatus are that constant use of a multimeter's continuity function and careful attention to detail in assembly, while appearing to be tedious and time consuming, save time and many frustrations in the long run.

CHAPTER 4: DATA ACQUISITION

4.1 INTRODUCTION

Chapter 4 presents the test campaigns, procedures and general results of the data taken on the experimental apparatus. Section 4.2 discusses the test campaigns performed. They include (1) Atmospheric Pressure Testing in Air; (2) Varied Pressure Testing in Different Fill Gases; (3) Below Atmospheric Pressure Testing; and (4) Specific Testing that was not originally identified and was deemed necessary as testing progressed. The variable parameters in the test campaigns are also discussed. Section 4.3 discusses the procedural processes used for data acquisition. Section 4.4 briefly discusses the test data results and the format of the data sheets provided in Appendix E.

4.2 TEST CAMPAIGNS

There are several variable parameters for the experimental apparatus. They are:

(1) The power input to the Heater Rod System;

(2) The controlling temperatures of the Boundary Condition Box System;

(3) The heat transfer medium in the Containment Vessel; and

(4) The operating pressure of the heat transfer medium.

These parameters were varied to enhance (accentuate) or eliminate each of the heat transfer mechanisms individually. This section will discuss the test campaigns executed with the experimental apparatus and the reasoning behind their selection.

The first parameter is the power input to the Heater Rods. The power is controlled by the temperature of a centrally located heater rod (Position 4-4) with the controller/alarm unit (ECS Model 6400-K-4-1-1-2-1). The controlling operating power ranges from 70°C to 250°C. For physical reasons, the minimum is established to ensure that the apparatus has a high enough power input for accurate temperature measurement; the maximum is to ensure that neither the maximum temperature design limitation of 370°C of the heater rods nor the maximum controller/alarm unit voltage delivery of 125 Volts is reached or exceeded. Note that the centrally located heater rod is not usually the hottest heater rod in the array. For fundamental heat transfer reasons, low operating temperatures accentuate convection while high temperatures accentuate radiation.

The second parameter is the controlling temperatures of the Boundary Condition Box. The box temperatures include each side of the box and each end of the box. The box sides temperatures were capable of being controlled with individual Omega 9111 Microprocessors, and the box ends temperatures were capable of being controlled with individual Omega 9111A Microprocessors. The box sides temperatures were not actually controlled in any of the Test Campaigns. It was not necessary since the axial temperature variation of each individual box side from the center to its own end was less than 2 degrees. The box ends temperatures were controlled for one matrix in Test Campaign 1. Both ends were controlled with thermocouples attached to the ends of the heater rod located in Position 2-7. Controlling the temperatures of the box ends did not produce useable results because the box end heaters' power input was not measured or quantified. Additionally, the heat from these end heaters adversely affected the temperature profile by adding heat to the outer ring of the array causing the temperature of the heater rod ends in the outer ring of the array to be higher than the centerline temperature. Consequently, the end heaters were not utilized further. As a whole, the box temperatures are not considered a controlled variable parameter in the Test Campaigns.

The third parameter is the heat transfer medium in the fuel array and the Containment Vessel. The variable mediums are Air, Nitrogen, Helium, and Argon. One reason these gases were chosen is due to their practical application in transportation casks. The other reason is due to their varied densities and thermal conductivities. A gas with a high thermal conductivity will accentuate conduction, and a gas with a high density will accentuate convection. The advantages and disadvantages of each heat transfer medium are as follows. Air is advantageous because it is inexpensive (free) and ubiquitous; however its purity level is unquantified. Nitrogen is inexpensive, does not leak excessively due to its large molecular size, and is a good heat transfer medium; however, it is not a noble gas and could possibly react with the spent nuclear fuel and become a carrier for radioactivity. Argon is reasonably priced, does not leak excessively due to its large molecular size, has similar heater transfer characteristics to Nitrogen, and is a noble gas and therefore not a potential carrier for radioactivity. Helium is comparatively expensive, is an exceptionally good heat transfer medium (high thermal conductivity), and is a noble gas and therefore not a potential carrier for radioactivity; however, it leaks easily due to its small molecular size.

The fourth parameter is the operating pressure of the heat transfer medium in the Containment Vessel. The operating pressures are below atmospheric pressure (approximately 24 inches of mercury), atmospheric pressure (0 psig), and above atmospheric pressure (15 psig). The pressure range was chosen to accentuate convection with high pressures (above atmospheric pressure) and to minimize convection with low pressures (below atmospheric pressure). Additionally, the pressure range was specified to ensure that the experimental pressure was maintained in the continuum regime shown in Figure 4-1. A higher operating pressure would have been desirable to further increase the convection effect; however, even though the Containment Vessel is rated for a

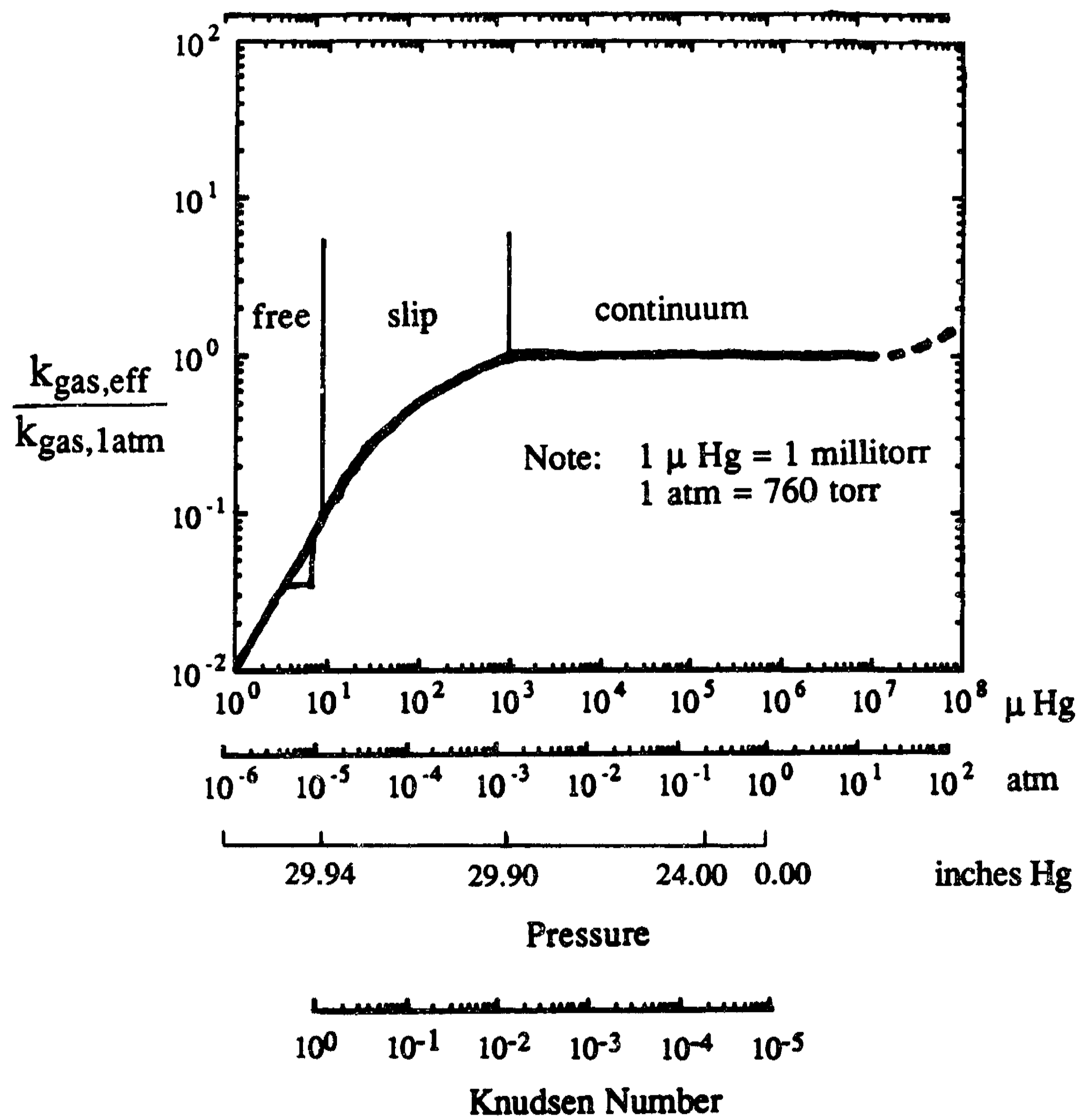

Figure 4-1: Effective Gas Conductivity in a Typical PWR Assembly as a function of Vacuum Pressure, including: Free-Molecular Flow (P < 29.94 inches Hg), Slip Flow (29.94 inches Hg < P < 29.90 inches Hg), and Continuum Regime (P > 29.90 inches Hg) [M-1]

maximum operating pressure of 75 psig, the power and thermocouple penetrations do not have a certified rating and due to safety concerns could not be operated above 20 psig. Rated penetrations could not be purchased due to budget constraints.

The data acquisition is categorized into four Data Acquisition Campaigns in which these parameters are varied. The Campaigns are: (1) Atmospheric Pressure Testing in Air; (2) Varied Pressure Testing in Different Fill Gases; (3) Below Atmospheric Pressure Testing; and (4) Specific Testing that was not originally identified and was deemed necessary as testing progressed. These campaigns were broken into matrices to vary the parameters further.

Test Campaign 1 Matrix 1 was performed at atmospheric pressure in air at 14 Heater Rod power levels with the controlling temperature ranging from 40°C to 250°C without the Boundary Condition Box side or end heaters operating and 10 Heater Rod power levels with the controlling temperature ranging from 70°C to 250°C with the Boundary Condition Box end heaters operating. The data acquisition in Test Campaign 1 Matrix 1 prior to May 7, 1991 is the Debugging Phase. This Phase is discussed in Section 4.5. The purpose of Test Campaign 1 Matrix 1 is to produce a base set of data.

Test Campaign 2 Matrix 1 was performed at above atmospheric pressure (15 ± 3 psig) in three different heat transfer mediums (Nitrogen, Argon, and Helium) at 9 Heater Rod power levels with the controlling temperature ranging from 70°C to 250°C without the Boundary Condition Box side or end heaters operating. The purpose of Test Campaign 2 Matrix 1 is to produce a set of data that accentuates conduction with Helium and accentuates convection with Argon and increased pressure.

Test Campaign 3 Matrix 1 was performed at below atmospheric pressure (24 ± 2 in. Hg) in air at 9 Heater Rod power levels with the controlling temperature ranging from 70°C to 250°C without the Boundary Condition Box side or end heaters operating. The purpose of Test Campaign 3 Matrix 1 is to produce a set of data that minimizes convection.

Test Campaign 4 identified, after testing had begun, additional tests that should be performed. Test Campaign 4 Matrix 1 expanded upon Test Campaign 2 Matrix 1 with above atmospheric pressure testing in the three heat transfer mediums with 6 additional Heater Rod power levels with a controlling temperature ranging from 70°C to 240°C. Test Campaign 4 Matrix 2 expanded upon Test Campaign 3 Matrix 1 with below atmospheric pressure testing in air with 5 additional Heater Rod power levels with a controlling temperature ranging from 140°C to 240°C.

A summary of the Test Campaigns is provided in Table 4-1. This table specifies each test with the heat transfer medium and pressure, Boundary Condition Box controlling temperature, Heater Rod controlling temperature, a Run Identification Number, and the date that the test was completed. Note that some of the tests were performed more than once, which is denoted by multiple dates under the "Date Completed" column in Table 4-1. Each combination of test parameters was assigned a Run Identification Number to allow easy identification of the parameters that apply to that set of tests. The Run Identification Number legend is given in Table 4-2.

Table 4-1: Test Campaign Summary (page 1 of 4)

Test Campaign No. 1 - Atmospheric Pressure Air Testing

Matrix No. 1 - Uniform Power Input into Heater Rods

Vessel Pressure (psig)	Fill Gas	Box Temperature (deg C)	Central Heater Rod Temperature (deg C)	Run I.D. No.	Date Completed
0 psig	Air	Not Controlled	40	11X0XXX040	04/30/91*
			50	11X0XXX050	04/30/91*
			70	11X0XXX070	06/01/91
			75	11X0XXX075	5/1* 5/23
			100	11X0XXX100	4/22* 5/24 6/3
			125	11X0XXX125	5/1* 5/24
			140	11X0XXX140	05/20/91
			150	11X0XXX150	4/25* 5/27 6/4&5
			175	11X0XXX175	5/2* 5/27
			190	11X0XXX190	05/20/91
			200	11X0XXX200	4/28* 5/28 6/8
			225	11X0XXX225	5/2* 5/28
			240	11X0XXX240	5/17 5/21
			250	11X0XXX250	4/29* 5/21 5/29
0 psig	Air	Guard (end) Heaters Controlled by Position 2-7	70	11X0XXX070E	5/4* 5/7
			80	11X0XXX080E	5/6* 5/8
			90	11X0XXX090E	5/6* 5/9
			100	11X0XXX100E	05/10/91
			125	11X0XXX125E	05/11/91
			150	11X0XXX150E	05/12/91
			175	11X0XXX175E	05/12/91
			200	11X0XXX200E	05/13/91
			225	11X0XXX225E	5/2* 5/14
			250	11X0XXX250E	5/4* 5/15

* As of 05/07/91, Experimental Apparatus modified to include a thermocouple under each box side heater. Indicated data sets taken before this date consequently do not include these additional thermocouple readings.

Table 4-1: Test Campaign Summary (page 2 of 4)

Test Campaign No. 2 - Various Pressure Testing in Different Fill Gases

Matrix No. 1 - Above Atmospheric Pressure Testing using the following gases:

1. Nitrogen (N_2)
2. Argon (Ar)
3. Helium (He)

- Uniform Power Input into Heater Rods

Vessel Pressure (psig)	Fill Gas	Box Temperature (deg C)	Central Heater Rod Temperature (deg C)	Run I.D. No.	Date Completed
15 psig	N_2	Not Controlled	70	21NPXXX070	06/09/91
			85	21NPXXX085	06/09/91
			100	21NPXXX100	06/10/91
			125	21NPXXX125	06/11/91
			150	21NPXXX150	06/11/91
			175	21NPXXX175	06/11/91
			200	21NPXXX200	06/12/91
			225	21NPXXX225	6/13 7/10
			250	21NPXXX250	06/13/91
15 psig	Ar	Not Controlled	70	21APXXX070	07/10/91
			85	21APXXX085	07/11/91
			100	21APXXX100	07/11/91
			125	21APXXX125	07/12/91
			150	21APXXX150	07/12/91
			175	21APXXX175	07/12/91
			200	21APXXX200	07/13/91
			225	21APXXX225	07/13/91
			250	21APXXX250	07/14/91
15 psig	He	Not Controlled	70	21HPXXX070	06/14/91
			85	21HPXXX085	06/14/91
			100	21HPXXX100	06/15/91
			125	21HPXXX125	06/16/91
			150	21HPXXX150	06/16/91
			175	21HPXXX175	06/17/91
			200	21HPXXX200	06/17/91
			225	21HPXXX225	7/4 7/6
			250	21HPXXX250	canceled

Table 4-1: Test Campaign Summary (page 3 of 4)

Test Campaign No. 3 - Below Atmospheric Pressure Testing

Matrix No. 1
- Below Atmospheric Pressure Testing
- Uniform Power Input into Heater Rods

Vessel Pressure (in Hg)	Fill Gas	Box Temperature (deg C)	Central Heater Rod Temperature (deg C)	Run I.D. No.	Date Completed
24 in Hg	Air	Not Controlled	70	31XVXXX070	07/22/91
			85	31XVXXX085	07/23/91
			100	31XVXXX100	7/23 7/28
			125	31XVXXX125	7/24 7/29
			150	31XVXXX150	07/25/91
			175	31XVXXX175	07/25/91
			200	31XVXXX200	07/26/91
			225	31XVXXX225	07/27/91
			250	31XVXXX250	07/27/91

Test Campaign No. 4 - Specific Testing

Matrix No. 1
- Above Atmospheric Pressure Testing using the following gases:
  1. Nitrogen (N_2)
  2. Argon (Ar)
  3. Helium (He)
- Uniform Power Input into Heater Rods

Vessel Pressure (psig)	Fill Gas	Box Temperature (deg C)	Central Heater Rod Temperature (deg C)	Run I.D. No.	Date Completed
15 psig	N_2	Not Controlled	70	41NPXXX070	07/06/91
			115	41NPXXX115	07/07/91
			140	41NPXXX140	07/08/91
			165	41NPXXX165	07/08/91
			190	41NPXXX190	07/09/91
			240	41NPXXX240	07/09/91

Table 4-1: Test Campaign Summary (page 4 of 4)

Test Campaign No. 4 - Specific Testing (continued)

Matrix No. 1 (continued)

Vessel Pressure (psig)	Fill Gas	Box Temperature (deg C)	Central Heater Rod Temperature (deg C)	Run I.D. No.	Date Completed
15 psig	Ar	Not Controlled	70	41APXXX070	07/14/91
			115	41APXXX115	07/15/91
			140	41APXXX140	07/15/91
			165	41APXXX165	07/16/91
			190	41APXXX190	07/16/91
			240	41APXXX240	07/17/91
15 psig	He	Not Controlled	70	41HPXXX070	07/01/91
			115	41HPXXX115	07/01/91
			140	41HPXXX140	07/02/91
			165	41HPXXX165	07/03/91
			190	41HPXXX190	07/03/91
			240*	41HPXXX232	07/05/91

Matrix No. 2

- Below Atmospheric Pressure Testing
- Uniform Power Input into Heater Rods

Vessel Pressure (in Hg)	Fill Gas	Box Temperature (deg C)	Central Heater Rod Temperature (deg C)	Run I.D. No.	Date Completed
24 in Hg	Air	Not Controlled	140	42XVXXX140	07/29/91
			165	42XVXXX165	07/30/91
			190	42XVXXX190	07/31/91
			215	42XVXXX215	07/31/91
			240	42XVXXX240	8/2 8/3

* Control Setpoint was modified to 232°C due to the inability of the apparatus in its present electrical configuration to reach 240°C.

Table 4-2: Run Identification Number Legend

Run ID No. Key: CMFPBBBHHHE

Alphabetic Designation	Meaning in Run ID No.	
C	Campaign Number	
M	Matrix Number	
F	Fill Gas Identifier	X = Air N = Nitrogen A = Argon H = Helium
P	Containment Pressure	0 = Atmospheric Pressure V = Below Atmospheric Pressure (24" Hg ± 2) P = Above Atmospheric Pressure (15 psig ± 3)
BBB	Boundary Condition Box (Sides) Controlling Temperature (Note: XXX means that the BCB is NOT Controlled)	
HHH	Central Heater Rod (Position 4-4) Controlling Temperature	
E	End Heater Operating Status	Blank = not operating E = operating

Example: Run ID No. 31XV100150 means
Campaign - 3; Test Matrix - 1; Fill Gas - Air;
Pressure - Below Atmospheric (24" Hg ± 2);
Boundary Condition Box (Sides) Temperature - 100°C;
Central Heater Rod Controlling Temperature - 150°C;
Boundary Condition Box End Heaters - not operating.

4.3 TEST PROCEDURES

This section describes the procedures used during data acquisition. This information was recorded in the Operating Log for the experiment.

A computer program was written by S. Friedenthal and the author to aid in data acquisition and data presentation. The computer program is written in the language Hewlett Packard Basic 5.13. A copy of the data acquisition program for temperature measurement of the experimental apparatus is provided in Appendix D. The program scans each of the multiplexer channels one hundred times and takes an average of each channels' readings. After thermocouple data acquisition, the program requires user input of the Heater Rod System's voltage and current. The program also requires user input to assign a run identification number. After the user inputs the required information into the computer program, a printout of the formatted data is provided. The program determines the average of each multiplexer channel temperature with its corresponding channel number and presents the data formatted in an 8x8 array for the corresponding heater rod thermocouple readings, a box format for the Boundary Condition Box side thermocouple readings, and a list of the corresponding other thermocouple readings under their appropriate heading: Containment Vessel environment temperatures; and Heater Rod end temperatures. The program saves the data in a file identified by the run identification number. This computer program was used for each set of data taken.

There are essentially three procedural processes to be followed in preparing the experimental apparatus for data acquisition. They are:

(1) the Heater Rod System Operating Process,

(2) the Containment Vessel Vacuum System Operating Process, and

(3) the Containment Vessel Pressure System Operating Process.

Each of these processes is discussed below.

The Heater Rod System Operating Process is considered the basic process for operating the experimental apparatus. It is utilized each time the experimental apparatus is prepared for data acquisition. This process requires only the Heater Rod System to be in-service and was the only process used in Test Campaign 1 Matrix 1, Atmospheric Air Testing. Power is provided to the heater rods through a power controller, ROD-C-1 (ECS Model 6414). Section 3.6 discusses the Heater Rod System, and an electrical drawing of the system is provided in Figure 3-13. Prior to allowing power into the Heater Rods, the setpoint for the system's alarm, ROD-A-1 (ECS Model 6460), must be set 10° higher than the controlling setpoint for the particular data acquisition run. Upon setting this alarm setpoint, the controlling setpoint is set, and power is provided to the heater rods automatically. It takes approximately 7 hours for the experimental apparatus to reach equilibrium at a nominal power input of 200 Watts. This was determined by plotting the Boundary Condition Box Top temperature as a function of time for several initial runs. When the experimental apparatus reaches equilibrium, the Data Acquisition System is used to take a set of data with the data acquisition program. After the test data results are printed out, the alarm and control setpoints are increased (decreased) to the next desired setpoints, repeating the process described above.

The Containment Vessel Vacuum System Operating Process is used in conjunction with the Heater Rod System Operating Process to prepare the experimental apparatus for below atmospheric pressure operation. This process is also utilized in the Containment Vessel Pressure System Operating Process to evacuate the Containment Vessel in order to create an effectively pure fill gas medium by evacuating and filling the Vessel twice in succession. The Containment Vessel Vacuum System Operating Process requires the Containment Vessel Vacuum System to be in-service. Section 3.5 discusses the Containment Vessel Vacuum System, and a Containment Vessel System drawing is provided in Figure 3-11. The system is placed in-service by starting the vacuum pump (CV-VP-1), and then immediately opening the system's isolation valve (CV-VAL-4) between the vacuum pump and the containment vessel. The Heater Rod System Operating Process is implemented while the vacuum pump is operating (or still operational after completion of the previous Test Matrix). The vacuum pump should continue to operate until the Containment Vessel Compound Gauge (CV-PG-1) indicates approximately 25 inches Hg. During the time that the vacuum pump is operating, the oil level and temperature of the pump should be monitored. Upon reaching the desired low pressure, the Containment Vessel Vacuum System is taken out-of-service by operating CV-VAL-4 to isolate the Containment Vessel and stopping the vacuum pump, CV-VP-1.

The Containment Vessel Pressure System Operating Process is used in conjunction with both the Heater Rod System Operating Process and the Containment Vessel Vacuum System Operating Process to prepare the experimental apparatus for above atmospheric pressure operation. The Containment Vessel Pressure System Operating Process first requires the Containment Vessel Pressure System in-service. Section 3.5 discusses the Containment Vessel Pressure System, and a Containment Vessel System drawing is provided in Figure 3-11. The system is placed in-service by opening the system's isolation valve (CV-VAL-1) between the compressed gas cylinder and the containment vessel and carefully regulating the fill gas flow by opening the compressed gas cylinder's isolation valve (CV-VAL-3). The Containment Vessel Pressure System is required to operate until the Containment Vessel Compound Gauge (CV-PG-1) indicates at least 5 psig. Then the system is removed from service, in this case only, by operating (closing) CV-VAL-1 and then quickly operating (closing) CV-VAL-3. This method is used to eliminate impurities that may exist in the gas line and to ensure the gas line is filled with the desired fill gas.

The next step in the process requires the Containment Vessel Vacuum System to be in-service utilizing the Containment Vessel Vacuum System Operating Process with noted changes. The Containment Vessel Vacuum System is used to create an effectively pure fill gas medium. In this process, the vacuum pump is required to operate until the

Containment Vessel Compound Gauge (CV-PG-1) indicates a vacuum in excess of 25 inches of mercury. At this point, the Containment Vessel Vacuum System Operating Process should be completed by taking the Containment Vessel Vacuum System out-of-service. Now the Containment Vessel Pressure System is placed back in-service. This time the Containment Vessel Pressure System is required to operate until the Containment Vessel Compound Gauge (CV-PG-1) indicates 20 psig. Then the system is immediately removed from service by operating (closing) CV-VAL-3 and then operating (closing) CV-VAL-1. The gas line regulator should indicate positive pressure which denotes that the gas line is pressurized with the desired fill gas. The Vacuum and Pressure Processes are repeated a second time to ensure an effectively pure fill gas medium. The Heater Rod System Operating Process is implemented after the final Pressure Process is completed (or still operational after completion of the previous Test Matrix).

Only three basic operating processes were needed to prepare the experimental apparatus for data acquisition as specified for the Test Campaigns. The test results are discussed in the next section.

4.4 TEST RESULTS

Test Campaign 1 Matrix 1 provides a base set of data; Test Campaign 2 Matrix 1 and Test Campaign 4 Matrix 1 provide a set of data that accentuates conduction with Helium and accentuates convection with Argon and above atmospheric pressure operation; Test Campaign 3 Matrix 1 and Test Campaign 4 Matrix 2 provide a set of data that minimizes convection with below atmospheric pressure operation. The Test Campaigns were run with the controlling temperature ranging from 40°C to 250°C. This section presents all test results. The test data is analyzed in Chapter 5. A copy of each data set is provided in Appendix E.

The data sheet for each data set is formatted to show the temperature distribution in the 8x8 Heater Rod array and the Boundary Condition Box sides. The data sheet provides the time and date of data acquisition, the Heater Rod System's voltage drop, current and calculated power level, the Containment Vessel heat transfer medium, operating pressure and environment temperatures at 2 locations, and the temperature measured at the centerline of each Heater Rod, the centerline of each Boundary Condition Box side, and on the ends of 5 Heater Rods. A sample data sheet is provided in Figure 4-2 identifying the Heater Rod position designation.

The final composite test results are shown in Figure 4-3. This figure is a plot of the test data for each heat transfer medium and its operating pressure for the Heater

Date: Month Date, Year
Time: HH:MM:SS (military time)

Run ID No. CMFPBBBHHH (see Table 4-2 for guidance)

Voltage:	VV.V Volts	Fill Gas:	fill gas used
Current:	I.II Amps	Pressure:	PP psig (PP in Hg)
Power:	WW.WWW Watts		

Vessel Temperature: Box End - TT.T deg C
TC End - TT.T deg C

Heater Rod Temperature Distribution

(Note: {x-x} denotes Heater Rod position. Each rod position {x-x} corresponds to heater rod's central temperature {TTT.T})

1-1	1-2	1-3	1-4	1-5	1-6	1-7	1-8
2-1	2-2	2-3	2-4	2-5	2-6	2-7	2-8
3-1	3-2	3-3	3-4	3-5	3-6	3-7	3-8
4-1	4-2	4-3	4-4	4-5	4-6	4-7	4-8
5-1	5-2	5-3	5-4	5-5	5-6	5-7	5-8
6-1	6-2	6-3	6-4	6-5	6-6	6-7	6-8
7-1	7-2	7-3	7-4	7-5	7-6	7-7	7-8
8-1	8-2	8-3	8-4	8-5	8-6	8-7	8-8

Box Temperature Distribution

Top TT.T(epoxy) TT.TT(under htr)

Right TT.T(epoxy) TT.TT(under htr) Left TT.T(epoxy) TT.TT(under htr)

Bottom TT.T(epoxy) TT.TT(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	TTT.T	TTT.T	TTT.T	TTT.T	TTT.T

Figure 4-2: Sample Test Run Data Sheet

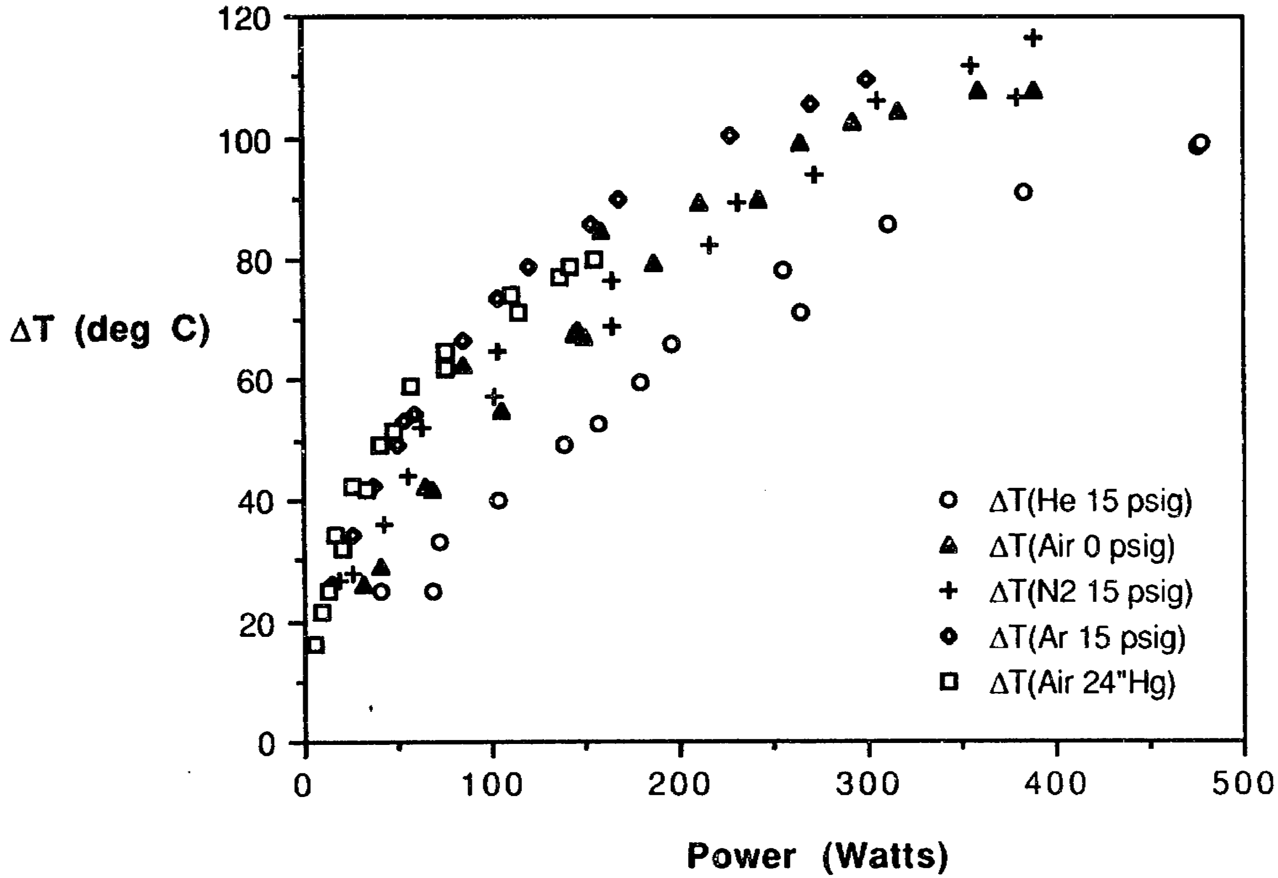

Figure 4-3: Differential Temperature as a Function of Power for the Experimental Data

Rod power levels showing the differential temperature between the hottest heater rod and the average box temperature as a function of power. Analysis of the data is performed in Chapter 5.

4.5 TEST DEBUGGING - LESSONS LEARNED

After assembly of the experimental apparatus, the apparatus was initially tested to ensure the components and instrumentation performed as designed. The initial testing results are provided in Appendix E Section 1. These results were examined to ensure that the apparatus provided the desired information. One problem was discovered and corrected and one discrepancy was noted.

The measured temperatures on the Boundary Condition Box walls were not as high as expected. It was determined that the method of attaching the thermocouples to the surface of the box did not provide an accurate measurement of the actual wall surface temperature. The thermocouples had been attached in a perpendicular orientation to the surface of each box side with high temperature and high thermally conductive epoxy. This method did not provide an accurate measurement because the thermocouple wire, being cooler than the thermocouple bead attached to the box, was conducting heat away from the thermocouple bead and the Boundary Condition Box surface to which the bead is attached. To correct this problem, a thermocouple was placed at the centerline under a strip heater on each box side and mechanically held in place. Each of these thermocouple beads is in direct contact with its appropriate box side. This was ensured by using a multimeter to verify continuity between each mechanically attached thermocouple. Approximately 10 inches of the thermocouple wire length was also placed under the strip heater to put it in the same thermal environment as the thermocouple bead. Since the thermocouple bead and wire are in a similarly heated region on the box surface, the measured surface temperature provides a more accurate measurement of the actual surface temperature.

For consistency with the initial testing (prior to May 7, 1991), the "epoxy" temperatures of the box sides are still recorded and documented on the Test Data Sheet as well as the "under heater" temperatures of the box sides. These temperatures are designated as such on the Test Data Sheet as "epoxy" and "under htr".

Also, it was discovered after comparing the differential temperatures on the five Heater Rods with centerline and end thermocouples over the series of testing, that the end thermocouple of the Heater Rod in Position 4-4 had become disconnected from the end of the rod. For consistency with the initial testing (prior to May 7, 1991), the temperature of the end thermocouple of Heater Rod Position 4-4 is still recorded and documented on the Test Data Sheet.

4.6 CHAPTER SUMMARY

The experimental apparatus was operated under four major campaigns where the parameters of the apparatus were varied to enhance or eliminate each of the heat transfer mechanisms. The operation included Air, Helium, Nitrogen, and Argon as the heat transfer mediums at a pressure range from below atmospheric pressure to above atmospheric pressure at a minimum of 9 different Heater Rod System power levels. The test data showed that each heat transfer mechanism could be enhanced by varying the operating parameters. In Chapter 5, an error analysis of the test data is provided, and the test data is also reduced using the lumped k_{eff}/h_{edge} model developed by R.D. Manteufel in his Doctoral Thesis at the Massachusetts Institute of Technology, 1991 in related work on this research project [M-1].

CHAPTER 5: DATA REDUCTION/ANALYSIS

5.1 INTRODUCTION

Chapter 5 presents the reduction and analysis of the test data obtained from the experimental apparatus. The complete set of the test data is provided in Appendix E. Section 5.2 presents the methods of data reduction which are based upon the lumped k_{eff}/h_{edge} model developed by R.D. Manteufel at MIT in 1991 in related work on this research project [M-1] and the Wooten-Epstein relationship developed at Battelle Memorial Institute in 1963 [B-2]. This section also describes the process used for data reduction and presents an example of this reduction using the Nitrogen/Air data. Appendix F contains the processes used for data reduction for Argon, Helium, and Below Atmospheric Pressure data. Section 5.3 presents the error analysis of the test data. Section 5.4 presents the comparison of the actual test data with the prediction results from the lumped k_{eff}/h_{edge} model and the Wooten-Epstein relationship. The test data is used to verify the lumped k_{eff}/h_{edge} model. Section 5.5 presents an assessment of the comparison.

5.2 METHODS OF REDUCTION

The methods of data reduction are based upon the lumped k_{eff}/h_{edge} model developed by R.D. Manteufel at MIT, 1991 in related work on this research project [M-1] and the Wooten-Epstein relationship developed at Battelle Memorial Institute in 1963 [B-2]. The characteristics of each of these methods are discussed individually.

The Wooten-Epstein relationship has been used by spent fuel shipping cask designers to predict the maximum spent fuel cladding temperature given the peak basket temperature. This relationship has flexibility because it has a variable input dependent of the size of the spent fuel array; however, it is also written specifically for application in a nitrogen heat transfer medium [B-2][M-1]. Therefore, in Section 5.4, this relationship's prediction is only compared with the Nitrogen/Air test data obtained from the experimental apparatus. A comparison with Argon or Helium is not applicable. A code was written by R.D. Manteufel (MIT) to use the Wooten-Epstein relationship to calculate the predicted differential temperature between the maximum heater rod temperature and the average wall temperature. A copy of the code is provided later in this section with the actual results from the code run.

The lumped k_{eff}/h_{edge} model predicts the maximum temperature in a heated rod array. The model assumes a uniform volumetric heat generation and uniform boundary temperature [M-1]. The lumped k_{eff}/h_{edge} model has built in flexibility to allow the user to specify the array geometry (shape and size) and the heat transfer medium. In Section 5.4, this model's predictions are compared with the Air/Nitrogen, Argon, Helium, and Below Atmospheric Pressure test data obtained from the experimental apparatus. The purpose of this comparison is to further the model validation begun in reference [M-1]. A lumped k_{eff}/h_{edge} code was written by R.D. Manteufel, using the computer software Mathematica, to calculate the predicted differential temperature between the maximum heater rod temperature and the average wall temperature. Since its publication in May 1991 [M-1], some changes have been made to the code.

The changes are:

(1) Instead of one program, the code is broken into 3 individual programs: (1) "gas.m"; (2) "keff.m"; and (3) "mit8x8.m". The first two programs are generic and contain the undefined variables of the lumped k_{eff}/h_{edge} model. "gas.m" provides the thermal properties of four heat transfer mediums: Air/Nitrogen, Argon, Helium, and Vacuum. "keff.m" provides the source code of the lumped k_{eff}/h_{edge} model. The third program, "mit8x8.m," provides input values specific to the experimental apparatus to yield the differential temperature prediction which can be evaluated by comparison with the test data.

(2) A modification was made in the "keff.m" code to the edge-to-interior heat transfer ratio,"f". The modification to "f" corrects the dependence of the thermal conductivity of the heat transfer medium from dependance on the maximum rod temperature to dependance on the average wall temperature.

(3) A modification was made in the "mit8x8.m" code to include the conduction factors for Argon and high and low Vacuums. Previously only conduction factors for Air/Nitrogen and Helium were presented.

The two methods of data reduction, the Wooten-Epstein relationship and the lumped k_{eff}/h_{edge} model, are applied to the data sets obtained from the experimental apparatus. The generic process for reduction applied to each data set and a detailed process of reduction for the Air/Nitrogen data set are presented in this section. The processes of reduction for Helium, Argon, and Below Atmospheric Pressure data sets are provided in Appendix F.

The generic process of data reduction has five steps. The steps are:

(1) Obtain the Average Wall Temperature as a function of Power.

(2) Evaluate the Wooten-Epstein relationship with the function obtained in Step 1.

(3) Evaluate the lumped k_{eff}/h_{edge} model with the function obtained in Step 1.

(4) Perform error analysis corrections to actual test data. The error analysis is presented in Section 5.3.

(5) Plot the outputs from Steps 2 and 3 along with the corrected test data (after error analysis) for each heat transfer medium. These plot are presented in Section 5.4.

The outputs from steps 2 and 3 provide the predicted differential temperatures between the maximum heater rod temperatures and the average wall temperatures as a function of power in the specified heat transfer medium that are plotted in Step 4 and presented in Section 5.4.

In Step 1, the user must obtain the average wall temperature as a function of power from the experimental data. The author used the Apple Macintosh software Cricket Graph to obtain the function. The powers and corresponding average wall temperatures obtained directly from the experimental data sets were input into Cricket Graph data files for different heat transfer mediums and then plotted individually. For each plot, a second order polynomial function curvefit was obtained for the average wall temperature as a function of power for each heat transfer medium. A curvefit was used to smooth the scatter in the data. This function is used in Steps 2 and 3.

In Step 2, the user must evaluate the Wooten-Epstein relationship with the function obtained in Step 1. The author used the Apple Macintosh software Mathematica to evaluate the Wooten-Epstein relationship, "WE.m". Prior to executing the program, the Average Wall Temperature function obtained from Step 1 must be input into "WE.m". After inputting the function, the program is executed. The output provides a table of the predicted differential temperatures between the maximum heater rod temperatures and the average wall temperatures as a function of power in the specified data set's heat transfer medium.

In Step 3, the user must evaluate the lumped k_{eff}/h_{edge} model with the function obtained in Step 1. The author used the Apple Macintosh software Mathematica to evaluate the lumped k_{eff}/h_{edge} model. Prior to executing the programs, the Average Wall Temperature function obtained in Step 1 and the heat transfer medium must be input into "mit8x8.m". Additionally, the user must ensure the desired heat transfer medium's conduction factor ("Fcond") is available in "mit8x8.m". After inputting the function and the heat transfer medium components, the three lumped k_{eff}/h_{edge} model programs are executed/evaluated in the following order:

First	"gas.m"
Second	"keff.m"
Third	"mit8x8.m".

The execution of the "mit8x8.m" program provides output, in a tabular form, of the predicted differential temperatures between the maximum heater rod temperatures and the average wall temperatures as a function of power in the specified data set's heat transfer medium.

To provide for an upper and lower error bound for the lumped k_{eff}/h_{edge} model, the three programs were executed two additional times using slightly different input values. The error bound accounts for the unknown exact value of the Heater Rod surface and Boundary Condition Box interior wall emissivities and the scatter in the average wall temperature plot in Step 1. The upper bound contains a rod and wall emissivity of 0.8 and a reduction of 10 degrees in the average wall temperature. The lower bound contains a rod and wall emissivity of 1.0 and an increase of 10 degrees in the average wall temperature. These error bounds were chosen to provide the maximum error in the prediction. The lumped k_{eff}/h_{edge} model upper bound program is called "mit8x8.up" and the lower bound program is called "mit8x8.lo".

In Step 4, the error analysis of the test data is performed. The error analysis is discussed in Section 5.3.

In Step 5, the user plots the outputs from Steps 2 and 3. The author used the Apple Macintosh software Cricket Graph to plot these outputs. The powers and corresponding predicted differential temperatures obtained from Steps 2 and 3 were input into Cricket Graph data files by individual heat transfer mediums and then plotted.

For each graph, a line plot was obtained for the differential temperature as a function of power for each heat transfer medium. These prediction curves are compared with the experimental powers and corresponding differential temperatures obtained from the experimental apparatus for each corresponding heat transfer mediums overlaid on the same graph. The results from this step will be shown in Section 5.4.

The detailed process of reduction for the Air and Nitrogen data sets will present the generic process described above in-use and will present each prediction method's input code with its corresponding output. The Air/Nitrogen data set includes the data taken at atmospheric pressure with air as the heat transfer medium (Appendix E.3) and the data taken above atmospheric pressure with nitrogen as the heat transfer medium (Appendix E.4). The Air (0 psig) and Nitrogen (15 psig) data were combined in the reduction/analysis for several reasons. First, the lumped k_{eff}/h_{edge} model only takes into account the radiation and conduction heat transfer mechanisms. For radiation in an essentially transparent gas, the density effect is minimal. Also, the thermal conductivity of air is less than 1% different than the thermal conductivity of nitrogen at the same temperature [K-2], and thermal conductivity is not a function of pressure [R-1]. Finally, note that convective heat transfer is not accounted for which is acceptable in these cases since the Rayleigh Number is below the critical value for the onset of significant natural convection [M-1 Section 3.3]. Hence these two sets of data were reduced and analyzed together as Air/Nitrogen.

The actual data reduction process applied to the Air/Nitrogen test data follows:

Air/Nitrogen Test Data Reduction Step 1.

In Step 1, the average wall temperature as a function of power is obtained for the Air/Nitrogen data. Using Cricket Graph, the actual power and average wall temperature obtained from the experimental apparatus for Air/Nitrogen are input into a data file. The data is then plotted in the form of Average Wall Temperature (y-axis) as a function of Power (x-axis) and a second order polynomial curve fit of this data provides the function input for Steps 2 and 3. The plotted Air/Nitrogen data with the curve fit is provided in Figure 5-1. The input function for Air/Nitrogen is:

$$y = 37.371 + 0.42445\,x - 3.8522(10)^{-4}\,x^2$$

where x is power and y is the average wall temperature.

Air/Nitrogen Test Data Reduction Step 2.

In Step 2, the Wooten-Epstein relationship is evaluated to provide a predicted differential temperature between the maximum heater rod temperature and the average wall temperature as a function of power for the Air/Nitrogen test data. Using

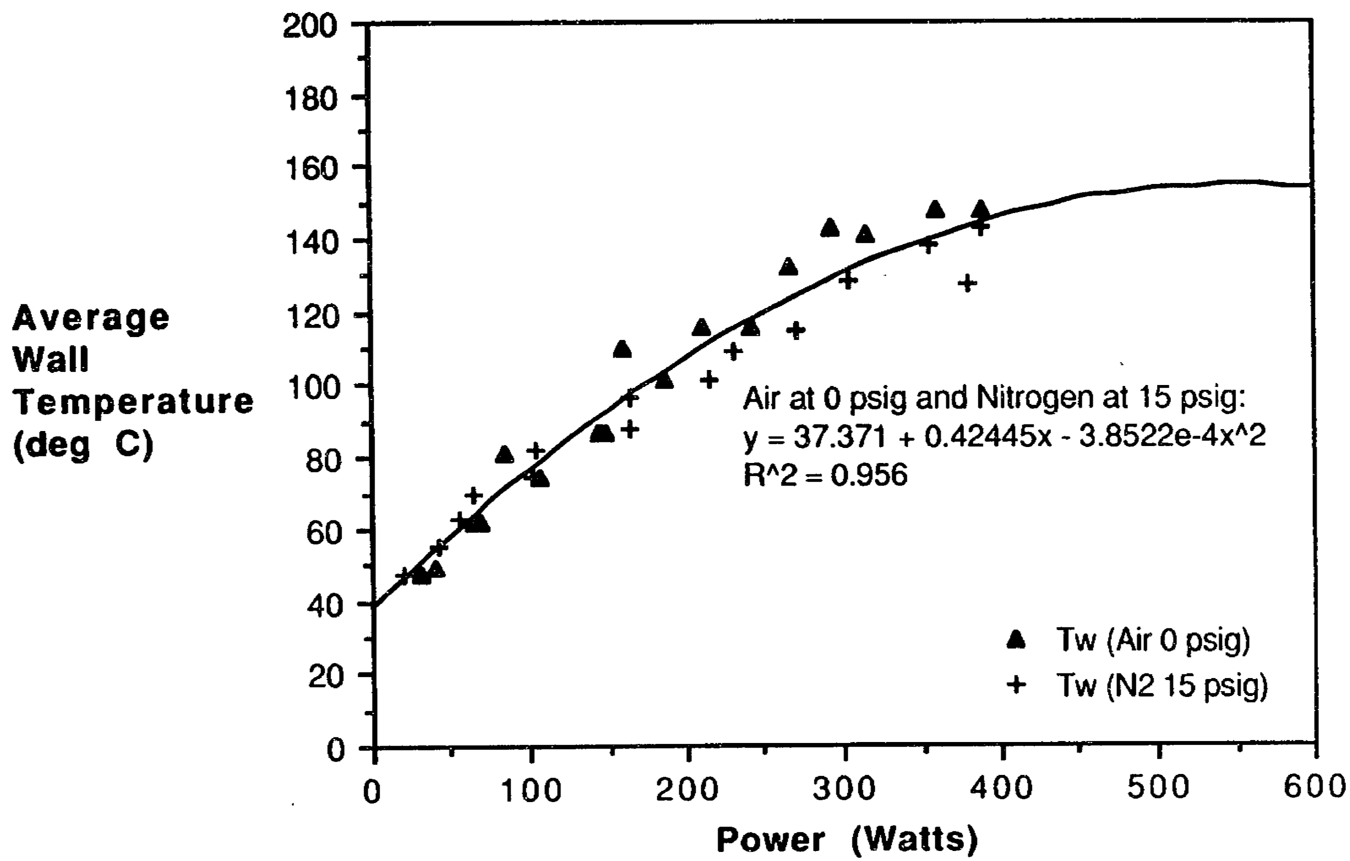

Figure 5-1: Average Wall Temperature of Air (0 psig) and Nitrogen (15 psig) Combined as a function of Power

Mathematica, the function obtained from Step 1 is input into the "WE.m" program in the following format:

37.371 + 0.42445 Q - 0.00038522 Q Q + 273

in the Input Section. Adding 273 converts the experimental temperature units (°C) to the units used in the theoretical prediction calculations (°K). After inputting the function, the "WE.m" program is executed/evaluated. The output results are in table form providing Power in the first column and Predicted Differential Temperature in the second column. Note: $\Delta T(°K) = \Delta T(°C)$. The "WE.m" program with its output results is provided in Table 5-1.

Air/Nitrogen Test Data Reduction Step 3.

In Step 3, the lumped k_{eff}/h_{edge} model is evaluated to provide a predicted differential temperature between the maximum heater rod temperature and the average wall temperature as a function of power for the Air/Nitrogen test data. Using Mathematica, the function obtained from Step 1 is input into the "mit8x8.m", "mit8x8.up" and "mit8x8.lo" programs in the following format:

37.371 + 0.42445 Q - 0.00038522 Q Q + 273

Table 5-1: Wooten-Epstein relationship code "WE.m" and its output results for Air (0 psig) and Nitrogen (15 psig) Combined

---

Input[1]:

```
(* Wooten-Epstein Solution for MIT 8x8 *)

ClearAll[ Q, Tw, Tm ];
La = 2 * 12 * 0.0254; (* axial length in meters *)
Lc = 4 9 1.33 3/8 0.0254; (* circumferential length*)
A = La Lc; (* area *)
er = 0.9;
ew = 0.9;
C1 = N[ 4 / ( 8+2 ) ];
C2 = 0.118 * 3.15459 (1.8^(4/3));
Fpeak = 1.0;

ΔTWE[ Q_, Tw_ ] := Tm-Tw /.
FindRoot[ Fpeak Q/A == C2 (Tm - Tw)^(4/3) +
  5.67 C1 / (1/er + 1/ew - 1) ( (Tm/100)^4 - (Tw/100)^4 ),
     {Tm, Tw+150} ]

TableForm[ Table[ { Q,ΔTWE[
     Q, 37.371 + 0.42445 Q - 0.00038522 Q Q + 273]},
     {Q,1,500, 50}]]
```

Output[1]:

1	1.16124
51	32.1677
101	52.0082
151	67.2676
201	79.8084
251	90.6226
301	100.339
351	109.391
401	118.102
451	126.72
501	135.444

in the Input Section. Adding 273 converts the experimental temperature units (°C) to the units used in the theoretical prediction calculations (°K). Additionally, the heat transfer medium (N2) is input into each of the "mit8x8" programs. The user should also ensure that the appropriate "Fcond" factor is available in each "mit8x8" program. Available means that the appropriate factor is not surrounded by comment characters, "(*" on the left side of "Fcond" for N2 and a second "*)" at the end of the line. After inputting these items, the lumped k_{eff}/h_{edge} model programs are ready to be executed/evaluated. First "gas.m" is executed; second "keff.m" is executed; third "mit8x8.m" is executed; fourth "mit8x8.up" is executed; and lastly "mit8x8.lo" is executed. The output results from "mit8x8.m", "mit8x8.up" and "mit8x8.lo" are in table form providing the Heat Transfer Medium (N2) in the first column, Power in the second column, and the Predicted Differential Temperature in the third column. Note: $\Delta T(°K) = \Delta T(°C)$. The "gas.m" program is provided in Table 5-2; the "keff.m" program is provided in Table 5-3; the "mit8x8.m" program with its output results is provided in Table 5-4; the "mit8x8.up" program with its output results is provided in Table 5-5; and the "mit8x8.lo" program with its output results is provided in Table 5-6.

Air/Nitrogen Test Data Reduction Step 4.

In Step 4, the error analysis of the test data is performed. The error analysis is discussed in Section 5.3.

Table 5-2: Lumped k_{eff}/h_{edge} Model Program 1 of 5: "gas.m" (page 1 of 2)

```
(* gas properties file *)

(* k in [W/m-K], T in [K] *)
ClearAll[atm,rho,new,alpha,beta,Pr,TCP,k,gas,gs,T,P];
k[ gs_, T_ ] := Which[
  gs == He,( a0 =  1.570322 10^-2;
          a1 =  6.7502003 10^-4;
          a2 = - 1.1871593 10^-6;
          a3 =  1.6446470 10^-9;
          a4 = - 8.0368411 10^-13;
  (((( a4 T + a3) T + a2) T + a1) T + a0)),
  gs == N2,( a0 =  7.7524326 10^-6;
          a1 =  1.0136155 10^-4;
          a2 = - 5.7331860 10^-8;
          a3 =  1.8781222 10^-11;
  ((( a3 T + a2) T + a1) T + a0)),
  gs == Ar,( a0 = - 2.4323518 10^-4;
          a1 =  7.2373876 10^-5;
          a2 = - 4.8841994 10^-8;
          a3 =  2.3910811 10^-11;
          a4 = - 4.5504155 10^-15;
  (((( a4 T + a3) T + a2) T + a1) T + a0)),
  gs == Vac, k[N2,T],
  gs == vac, k[N2,T],
  1==1,     dontknow ]

atm = 1.01 10^5

rho[gas_, T_, P_] := P MW[gas] / (8314.0 T)
new[gas_, T_, P_] := μ[gas,T] / rho[gas,T,P]
alpha[gas_,T_,P_] := k[gas,T]/(rho[gas,T,P] cp[gas,T])
beta[gas_,T_,P_]  := 1 / T
Pr[gas_,T_,P_]    := new[gas,T,P]/alpha[gas,T,P]

TCP[gas_,T_,P_]  := Which[
  gas == Vac, 0,
  gas == vac, 0,
   1 == 1, (9.81 beta[gas,T,P]/ (new[gas,T,P]
           alpha[gas,T,P])) ]
```

```
(* μ in [N s / m2 ] *)
μ[ gas_, T_ ] := Which[
  gas == He,  4.26688 10^-7 T^0.67306,
  gas == N2,  3.13545 10^-7 T^0.70852,
  gas == Ar,  2.9634  10^-7 T^0.76065,
  1==1,      dontknow ]


(* cp in [J/kg-K] *)
cp[ gas_, T_] := Which[
  gas == He, 5193.0,
  gas == N2,  793.963 T^0.047097,
  gas == Ar,  533.703 T^-0.0039,
  1==1,      dontknow ]

MW[ gas_ ] := Which[
  gas == He, 4.003,
  gas == N2, 28.06,
  gas == Ar, 39.94,
  1==1,      dontknow ]
```

Table 5-3: Lumped k_{eff}/h_{edge} Model Program 2 of 5: "keff.m" (page 1 of 2)

```
(* keff file *)

(* evaluate gas.m file before this file *)

ClearAll[ kc,kr,keff,kcw,krw,hcw,hrw,heffw,f,qp,qppw,
 Tw, Te, Tm, gas, Ra, Tf, Tfw, Q, geom, box, hex, cir,
 pdr, wpr, w, d, p, La, Lc, Fpeak, Fcond, Crad, Cradw1, Cradw2 ];

ΔTkeff[ gas_, Fpeak_, Q_, Tw_, La_, Lc_, d_, pdr_, wpr_, geom_,
 Fcond_, Crad_, Cradw1_, Cradw2_ ] := (

 Which[ geom == box, S = 4.321  N[Pi],
      geom == hex, S = 4.086  N[Pi],
      geom == cir, S = 4.000  N[Pi] ];

 qp    = Q Fpeak / La;
 qppw  = Q Fpeak / ( La Lc ) ;
 Fcondw = Fcond wpr / ( 0.5 + Fcond (wpr - 0.5 ) );
 w     = wpr pdr d;

 Te    = Tw + 10;
 Tm    = Tw + 20;

 (* iterate to solve *)
Do[
 Tf    = (Tm+Te)/2;
 Tfw   = (Te+Tw)/2;
 kc    = Fcond  k[ gas, Tf];
 kr    = Crad 0.0567 N[Pi] d 4 (Tf/100)^3;
 keff  = kc + kr;
 kcw   = Fcondw k[ gas, Tfw];
 krw   = Cradw1 0.0567 N[Pi] d 4 (Tfw/100)^3;
 f     = (kcw / wpr + krw ) /
    ( Fcond  k[ gas, Tfw] + Crad 0.0567 N[Pi] d 4 (Tfw/100)^3 );
 hcw   = kcw / ( w (1-f/2) );
 hrw   = Cradw2 0.0567 N[Pi] / pdr 4 (Tfw/100)^3 / (1-f/2);
 hedge = hcw + hrw;
 Te    = Tw + qppw /  hedge ;
 Tm    = Te + qp / ( S keff );,  {10} ];
```

```
(*
Print[ " gas   = ", gas];
Print[ " Tw    = ", Tw-273, " C,   = ", Tw, " K " ];
Print[ " Te    = ", Te-273, " C,   = ", Te, " K " ];
Print[ " Tm    = ", Tm-273, " C,   = ", Tm, " K " ];
Print[ " ΔT    = ", Tm-Tw, " C "];
Print[ " ΔTw   = ", Te-Tw, " C "];
Print[ " %ΔTw  = ", (Te-Tw)/(Tm-Tw) 100.0 ];
Print[ " %C    = ", (kc  / keff ) 100.0 ];
Print[ " %Cw   = ", (hcw / hedge) 100.0 ]; *)

{ gas, Q, Tm-Tw }  )
```

Table 5-4: Lumped k_{eff}/h_{edge} Model Program 3 of 5: "mit8x8.m" with its output results for Air (0 psig) and Nitrogen (15 psig) Combined

---

Input[1]:

```
(* mit 8x8 file *)

(* evaluate 'gas.m' and 'keff.m' files before this file *)

Fpeak = 1.0;
geom  = box;
La    = 2.0 12.0  0.0254;   (* axial length 2 ft *)
d     = (3.0/8.0) 0.0254;  (* 3/8 in rod diameter *)
pdr   = 1.33;
wpr   = 1.00;
w     = wpr pdr d;
p     = pdr d;
Lc    = 4 ( 8 p );           (* circumferential length *)

Fcond = 2.5;   (* SQ, p/d=1.33, N2 w/c *)
               (* SQ, p/d=1.33, Ar w/c *)
               (* SQ, p/d=1.33, Vac no better than 10 torr *)
(*  Fcond = 2.0;        (* SQ, p/d=1.33, He w/c *)   *)
(*  Fcond = 0.0,        (* SQ, p/d=1.33, Vac better than 1E-5 torr *) *)

(* SQ, p/d=1.33, er = 0.9, Crad = 0.45 *)
(* SQ, p/d=1.33, er = ew = 0.9, Cradw1 = 0.44, Cradw2 = 0.36 *)
Crad   = 0.45;
Cradw1 = 0.44;
Cradw2 = 0.36;


(* Atmospheric Air & Pressurized Nitrogen data combined *)
Table[ ΔTkeff[ N2, Fpeak, Q,
               37.371 + 0.42445 Q - 0.00038522 Q Q + 273,
               La, Lc, d, pdr, wpr, geom,
               Fcond, Crad, Cradw1, Cradw2 ],
               {Q, 1, 400, 20}]
```

Output[1]:

```
{{N2, 1, 1.03586}, {N2, 21, 19.3087}, {N2, 41, 34.0169},
 {N2, 61, 46.2298}, {N2, 81, 56.6114}, {N2, 101, 65.6041},
 {N2, 121, 73.5182}, {N2, 141, 80.58}, {N2, 161, 86.9596},
 {N2, 181, 92.7886}, {N2, 201, 98.1705}, {N2, 221, 103.189},
 {N2, 241, 107.911}, {N2, 261, 112.394}, {N2, 281, 116.684},
 {N2, 301, 120.822}, {N2, 321, 124.842}, {N2, 341, 128.775},
 {N2, 361, 132.645}, {N2, 381, 136.478}, {N2, 401, 140.292}}
```

Table 5-5: Lumped k_{eff}/h_{edge} Model Program 4 of 5: "mit8x8.up" with its output results for the Upper Error Bound for Air (0 psig) and Nitrogen (15 psig) Combined

---

Input[2]:

```
(* mit 8x8 file *)

(* evaluate 'gas.m' and 'keff.m' files before this file *)

Fpeak = 1.0;
geom  = box;
La    = 2.0 12.0  0.0254;   (* axial length 2 ft *)
d     = (3.0/8.0) 0.0254;  (* 3/8 in rod diameter *)
pdr   = 1.33;
wpr   = 1.00;
w     = wpr pdr d;
p     = pdr d;
Lc    = 4 ( 8 p );          (* circumferential length *)

Fcond = 2.5;  (* SQ, p/d=1.33, N2 w/c *)
              (* SQ, p/d=1.33, Ar w/c *)
              (* SQ, p/d=1.33, Vac no better than 10 torr *)
(*  Fcond = 2.0;      (* SQ, p/d=1.33, He w/c *)  *)
(*  Fcond = 0.0,      (* SQ, p/d=1.33, Vac better than 1E-5 torr *) *)

(* SQ, p/d=1.33, er = 0.8, Crad = 0.39 *)
(* SQ, p/d=1.33, er = ew = 0.8, Cradw1 = 0.37, Cradw2 = 0.30 *)
Crad   = 0.39;
Cradw1 = 0.37;
Cradw2 = 0.30;


(* Atmospheric Air & Pressurized Nitrogen data combined *)
Table[ ΔTkeff[ N2, Fpeak, Q,
              37.371 + 0.42445 Q - 0.00038522 Q Q + 273 - 10,
              La, Lc, d, pdr, wpr, geom,
              Fcond, Crad, Cradw1, Cradw2 ],
              {Q, 1, 400, 20}]
```

Output[2]:

```
{{N2, 1, 1.22123}, {N2, 21, 22.5896}, {N2, 41, 39.5876},
 {N2, 61, 53.5936}, {N2, 81, 65.4363}, {N2, 101, 75.6551},
 {N2, 121, 84.6221}, {N2, 141, 92.6051}, {N2, 161, 99.8034},
 {N2, 181, 106.37}, {N2, 201, 112.424}, {N2, 221, 118.06},
 {N2, 241, 123.358}, {N2, 261, 128.379}, {N2, 281, 133.179},
 {N2, 301, 137.801}, {N2, 321, 142.285}, {N2, 341, 146.664},
 {N2, 361, 150.967}, {N2, 381, 155.22}, {N2, 401, 159.446}}
```

Table 5-6: Lumped k_{eff}/h_{edge} Model Program 5 of 5: "mit8x8.lo" with its output results for the Lower Error Bound for Air (0 psig) and Nitrogen (15 psig) Combined

---

Input[3]:

```
(* mit 8x8 file *)

(* evaluate 'gas.m' and 'keff.m' files before this file *)

Fpeak = 1.0;
geom  = box;
La    = 2.0 12.0  0.0254;   (* axial length 2 ft *)
d     = (3.0/8.0) 0.0254;  (* 3/8 in rod diameter *)
pdr   = 1.33;
wpr   = 1.00;
w     = wpr pdr d;
p     = pdr d;
Lc    = 4 ( 8 p );         (* circumferential length *)

Fcond = 2.5;  (* SQ, p/d=1.33, N2 w/c *)
              (* SQ, p/d=1.33, Ar w/c *)
              (* SQ, p/d=1.33, Vac no better than 10 torr *)
(*  Fcond = 2.0;       (* SQ, p/d=1.33, He w/c *)  *)
(*  Fcond = 0.0,       (* SQ, p/d=1.33, Vac better than 1E-5 torr *) *)

(* SQ, p/d=1.33, er = 1.0, Crad = 0.51 *)
(* SQ, p/d=1.33, er = ew = 1.0, Cradw1 = 0.52, Cradw2 = 0.41 *)
Crad   = 0.51;
Cradw1 = 0.52;
Cradw2 = 0.41;


(* Atmospheric Air & Pressurized Nitrogen data combined *)
Table[ ΔTkeff[ N2, Fpeak, Q,
              37.371 + 0.42445 Q - 0.00038522 Q Q + 273 + 10,
              La, Lc, d, pdr, wpr, geom,
              Fcond, Crad, Cradw1, Cradw2 ],
              {Q, 1, 400, 20}]
```

Output[3]:

```
{{N2, 1, 0.884856}, {N2, 21, 16.6125}, {N2, 41, 29.416},
 {N2, 61, 40.1292}, {N2, 81, 49.2864}, {N2, 101, 57.2513},
 {N2, 121, 64.2832}, {N2, 141, 70.5739}, {N2, 161, 76.269},
 {N2, 181, 81.4819}, {N2, 201, 86.3028}, {N2, 221, 90.8045},
 {N2, 241, 95.0468}, {N2, 261, 99.0793}, {N2, 281, 102.944},
 {N2, 301, 106.677}, {N2, 321, 110.308}, {N2, 341, 113.865},
 {N2, 361, 117.371}, {N2, 381, 120.848}, {N2, 401, 124.314}}
```

Air/Nitrogen Test Data Reduction Step 5.

In Step 5, the output results from Steps 2 and 3 as well at the experimental results obtained in an Air/Nitrogen heat transfer environment are plotted. Using Cricket Graph, the powers and predicted differential temperatures are input into a data file. Each prediction is then line plotted in the form of Differential Temperature (y-axis) as a function of Power (x-axis) on the same graph. Then a scatter plot of the corrected test data (after error analysis) from Step 4 is overlaid on the predictions. This graph is presented in Section 5.4.

The processes of data reduction for Helium, Argon, and Below Atmospheric Pressure are provided in Appendix F. The process results include the plot and curve fit of the average wall temperature as a function of power and the lumped k_{eff}/h_{edge} code results for each heat transfer medium. The comparison of the predictions with the test data is provided in Section 5.4

5.3 ERROR ANALYSIS OF TEST DATA

An analysis of the possible errors in the test data from the experimental apparatus is presented in this section. There are two types of error: systematic and random. Each of these error types are discussed individually.

The systematic error accounts for the end heat losses in the experimental apparatus. The end heat loss was monitored on four Heater Rods with the thermocouples at the centerlines and attached to the ends of the rods. These rods are in Positions 1-1, 2-7, 5-5, and 7-3. A code was written for the Apple Macintosh software Mathematica by R.D. Manteufel (MIT, 1991) to determine the heat loss from the rod bundle out the ends of the experimental apparatus. The code takes the temperature differential between the four Heater Rod centerline thermocouples with their non-lead end attached thermocouples and weights their loss by the number of Heater Rods in their corresponding ring to determine the systematic error. This is necessary because the rod end temperatures vary with radial location within the Heater Rod array. The code was applied to the test data obtained from the experimental apparatus as a whole to obtain one error to be applied to the entire data set. A copy of the code and its results are provided in Appendix G. The systematic error for correcting the experimental test data for end heat losses is 11%.

The random error accounts for possible errors in measuring the current, voltage, and temperature in the system. These measured quantities are used to provide derived quantities such as power and differential temperature. The uncertainty associated with these derived quantities is estimated from the uncertainties of the direct measured quantities. "For any function

$$y = f(x_1, x_2, \ldots, x_i, \ldots, x_n)$$

the uncertainty in y, E_y, can be expressed as

$$(E_y)^2 = \sum_i^n (\delta f/\delta x_i)^2 (E_{x_i})^2$$

where x_i, i = 1,2,...,n, are the directly measured parameters, y, is the derived quantity from the directly measured parameters, and E represents the uncertainty" [F-1].

The random error has been approximated as described below since the current and voltage were not measured continuously during the acquisition of each data set and since a standard deviation was not calculated for each data point from the data set.

The uncertainty was calculated for two general cases of power: low power and high power. At a typical low power, the observed range in current indication about the mean was approximately 0.05 Amps, and the analogous observed differential voltage was approximately 1.4 Volts. The typical low power is 50 Watts (35.4 Volts x 1.40 Amps).

At a typical high power, the observed range in current indication about the mean was approximately 0.09 Amps, and the analogous observed differential voltage was approximately 2.0 Volts. The typical high power is 300 Watts (88.1 Volts x 3.40 Amps). The low power and high power uncertainties can be calculated from

$$(\Delta \text{Power})^2 = [(\Delta V)x(i)]^2 + [(\Delta i)x(V)]^2$$

Example: The low power uncertainty is

$$(\Delta \text{Power})^2 = [(1.4 \text{ Volts})x(1.40 \text{ Amps})]^2 + [(0.05 \text{ Amps})x(35.4 \text{ Volts})]^2$$

$$(\Delta \text{Power}) = 2.4 \text{ Watts}$$

The calculated uncertainties for low power and high power are 2.4 Watts and 10.4 Watts, respectively. These uncertainties are shown on the figures presented in Section 5.4 where the test data is compared with the lumped k_{eff}/h_{edge} model and the Wooten-Epstein relationship.

The uncertainty in the differential temperature of the hottest Heater Rod and the Boundary Condition Box average wall temperature has also been determined. As discussed in Section 3.2, the thermocouples have been calibrated with an uncertainty of 1.8°C. Therefore, the minimum uncertainty assigned to an individual temperature reading is 1.8°C. Since the Boundary Condition Box wall temperatures were averaged, the standard deviation of this average was calculated for the data sets with lowest and highest power for each analyzed group of data. The selected lowest and highest power data analyzed are identified in Table 5-7. The resulting standard deviations are shown in Table 5-8. The standard deviation of the average box wall temperature or 1.8°C, whichever is larger, was used with the calibration uncertainty for hottest Heater Rod (1.8°C) to calculate the uncertainty of the differential temperature for the data sets determined above. The resulting uncertainties are shown in Table 5-9. These uncertainties are shown on the figures presented in Section 5.4 where the test data is compared with the lumped k_{eff}/h_{edge} model and the Wooten-Epstein relationship.

Table 5-7: Selected Data Sets Analyzed for the Random Error Associated with Temperature

	Selected Data Sets by Run ID No.	
	Power (min)	Power (max)
Air/Nitrogen	41NPXXX070 07/06/91 22:48:54 Power = 19.3 Watts	21NPXXX250 06/13/91 15:34:43 Power = 389.7 Watts
Argon	21APXXX070 07/10/91 21:14:26 Power = 13.4 Watts	21APXXX250 07/14/91 08:27:18 Power = 299.5 Watts
Helium	21HPXXX070 06/14/91 11:32:08 Power = 41.7 Watts	41HPXXX232 07/05/91 20:55:22 Power = 582.5 Watts
Air (24 inches Hg)	31XVXXX070 07/22/91 12:33:43 Power = 5.6 Watts	31XVXXX250 07/27/91 11:07:13 Power = 154.7 Watts

Table 5-8: Standard Deviation of the Boundary Condition Box Average Wall Temperature for Selected Cases

$$\sigma^2 = \frac{\Sigma(x_i)^2}{n} - (x)^2 \qquad [L-2]$$

	σ of Average Wall Temperature (°C)	
	Power (min)	Power (max)
Air/Nitrogen	0.60	3.21
Argon	0.63	3.46
Helium	0.27	1.45
Air (24 inches Hg)	0.17	1.85

Table 5-9: Uncertainty in Differential Temperature of the Experimental Data for Selected Cases

$$\Delta(T_h - T_w) = [(\Delta T_h)^2 + (\Delta T_w)^2]^{1/2}$$

	Uncertainty in ΔT (°C)	
	Power (min)	Power (max)
Air/Nitrogen	2.55	3.68
Argon	2.55	3.90
Helium	2.55	2.55
Air (24 inches Hg)	2.55	2.58

5.4 COMPARISON OF TEST DATA TO PREDICTION

The comparison of the test data obtained from the experimental apparatus and the predictions from the lumped k_{eff}/h_{edge} model and the Wooten-Epstein relationship are presented in this section. Section 5.2 discussed the process of data reduction and Step 4 of that process discussed the actual plotting of the predictions of differential temperature as a function of power. The assessment of the comparisons of the test data and the theoretical predictions is presented is Section 5.5. The comparison of all the data sets with their corresponding lumped k_{eff}/h_{edge} model prediction is provided in Figure 5-2. Each data set is also presented and discussed individually.

The first comparison presented is the Air/Nitrogen data. Figure 5-3 provides a graphical comparison of the test data obtained from the experimental apparatus with the heat transfer mediums, Air at 0 psig and Nitrogen at 15 psig, that has been corrected for the heat loss out the ends of the apparatus (11%), the lumped k_{eff}/h_{edge} model prediction with its upper and lower bounds, and the Wooten-Epstein prediction. The test data shows good agreement with the predictions. The assessment of this comparison is presented in Section 5.5.

The second comparison presented is the Argon data. Figure 5-4 provides a graphical comparison of the test data obtained from the experimental apparatus with the heat transfer medium, Argon at 15 psig, that has been corrected for the heat loss out the

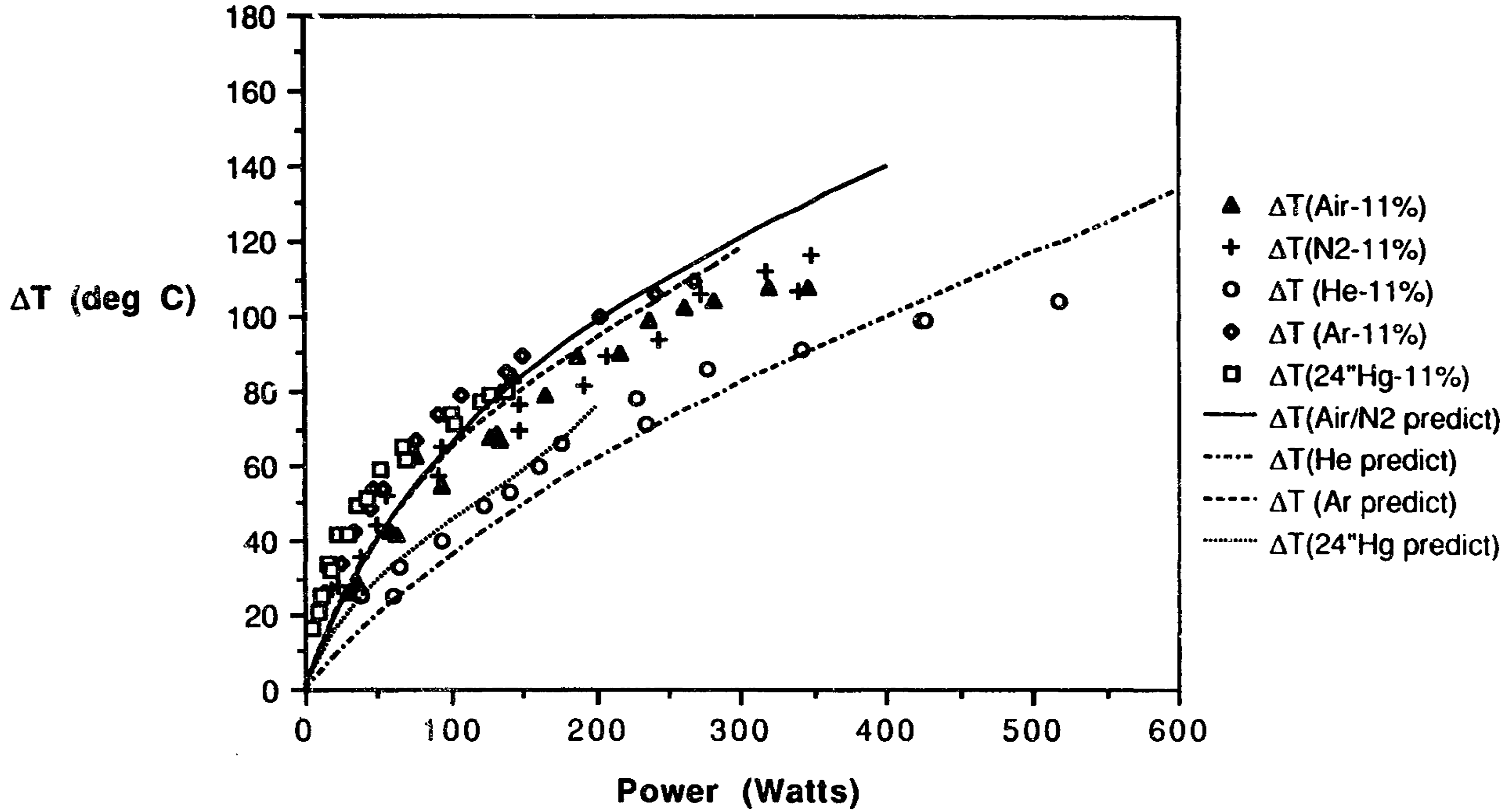

Figure 5-2: Actual and Predicted ΔT as a function of Power in Air/Nitrogen, Helium, Argon, and 24 inches Hg

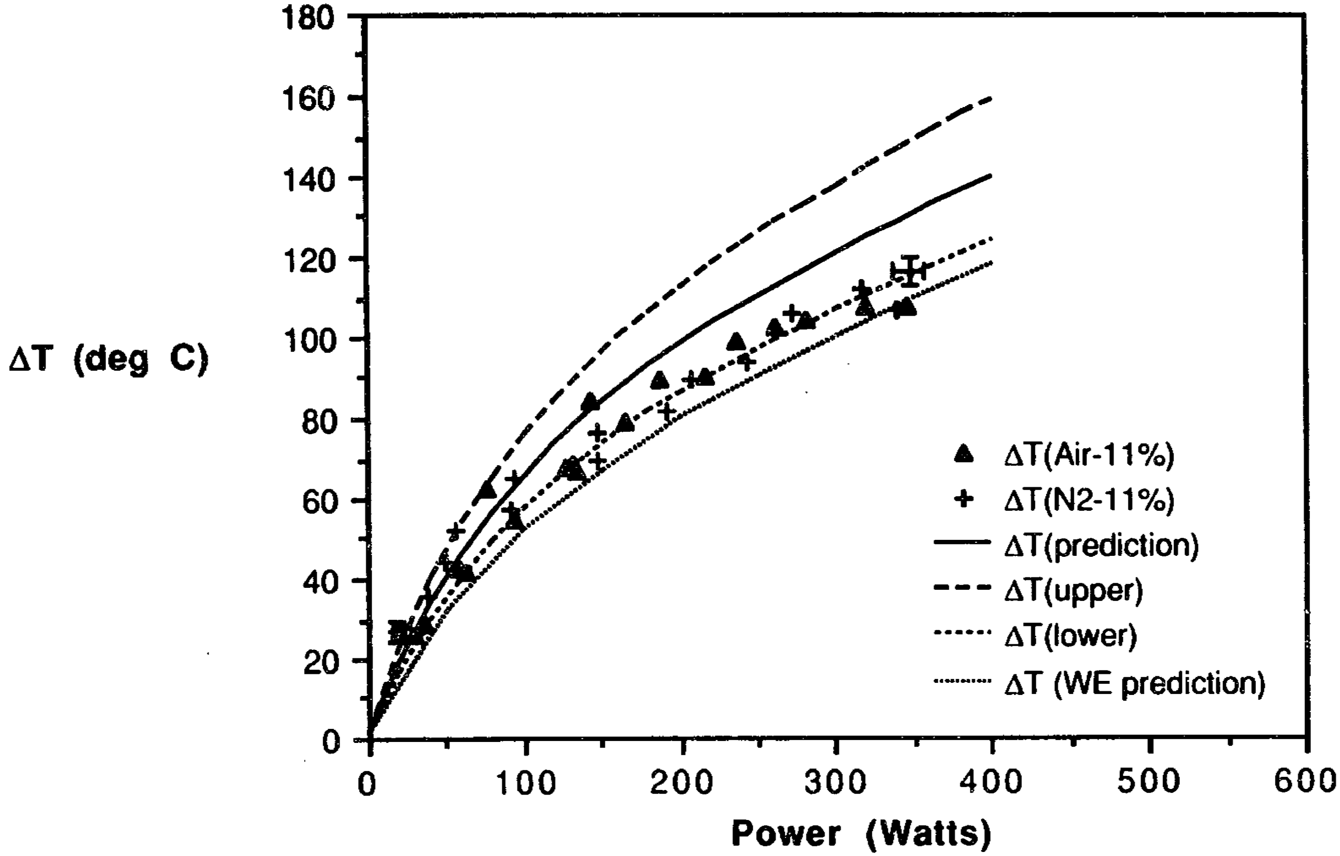

Figure 5-3: Actual and Predicted (with error bounds) ΔT as a function of Power in Air (0 psig) and Nitrogen (15 psig)

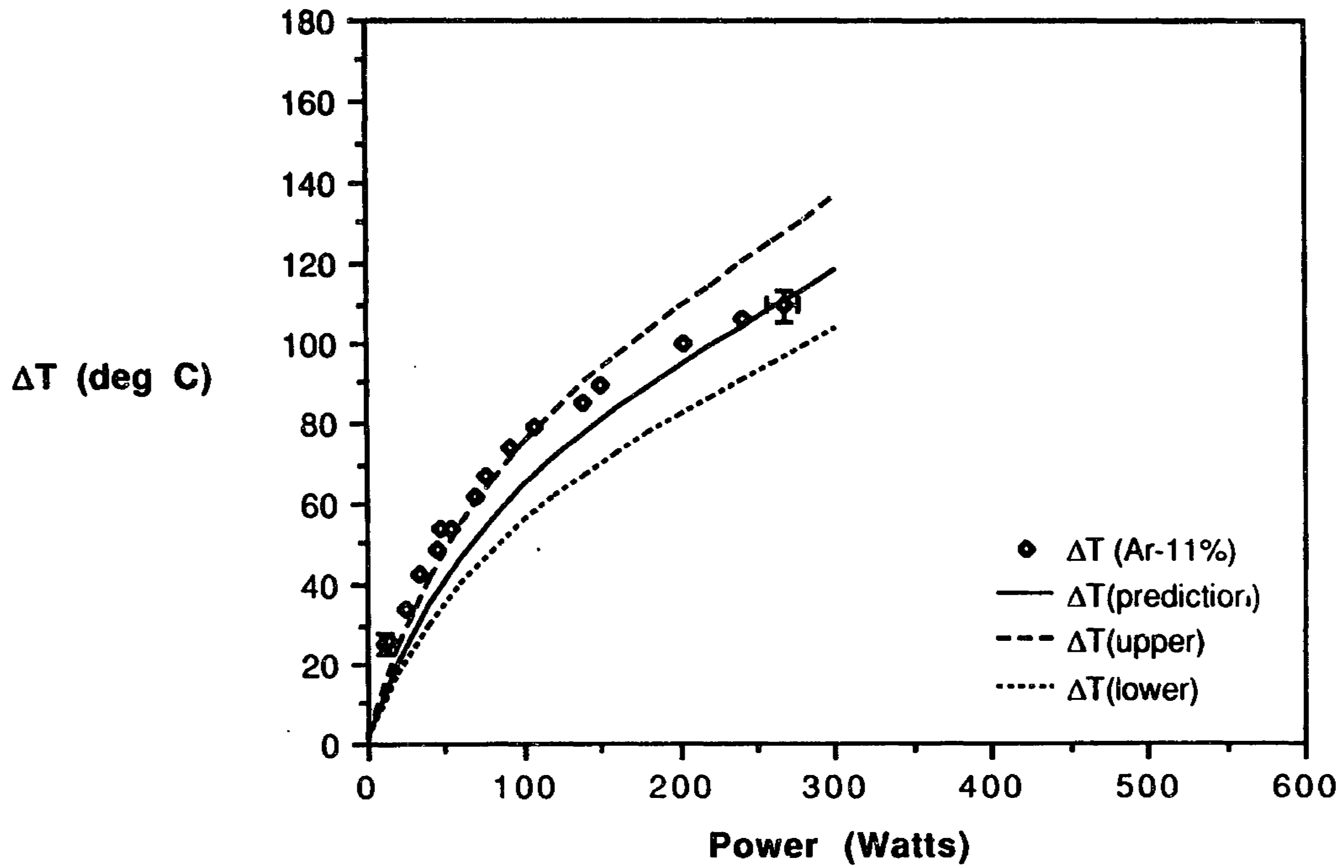

Figure 5-4: Actual and Predicted (with error bounds) ΔT as a function of Power in Pressurized Argon (15 psig)

ends of the apparatus (11%), and the lumped k_{eff}/h_{edge} model prediction with its upper and lower bounds. Recall that the Wooten-Epstein prediction is not applicable in this case. The test data shows good agreement with the prediction. The assessment of this comparison is presented in Section 5.5.

The third comparison presented is the Helium data. Figure 5-5 provides a graphical comparison of the test data obtained from the experimental apparatus with the heat transfer medium, Helium at 15 psig, that has been corrected for the heat loss out the ends of the apparatus (11%), and the lumped k_{eff}/h_{edge} model prediction with its upper and lower bounds. Recall that the Wooten-Epstein prediction is not applicable in this case. The test data shows good agreement with the prediction. The assessment of this comparison is presented in Section 5.5.

The fourth comparison presented is the Below Atmospheric Pressure data. Figure 5-6 provides a graphical comparison of the test data obtained from the experimental apparatus with at below atmospheric pressure (24 inches Hg)-with the initial heat transfer medium of air. The test data has been corrected for the heat loss out the ends of the apparatus (11%), and the lumped k_{eff}/h_{edge} model prediction with its upper and lower bounds. Recall that the Wooten-Epstein prediction is not applicable in this case. The test data does not show good agreement with the prediction. The assessment of this comparison is presented in Section 5.5.

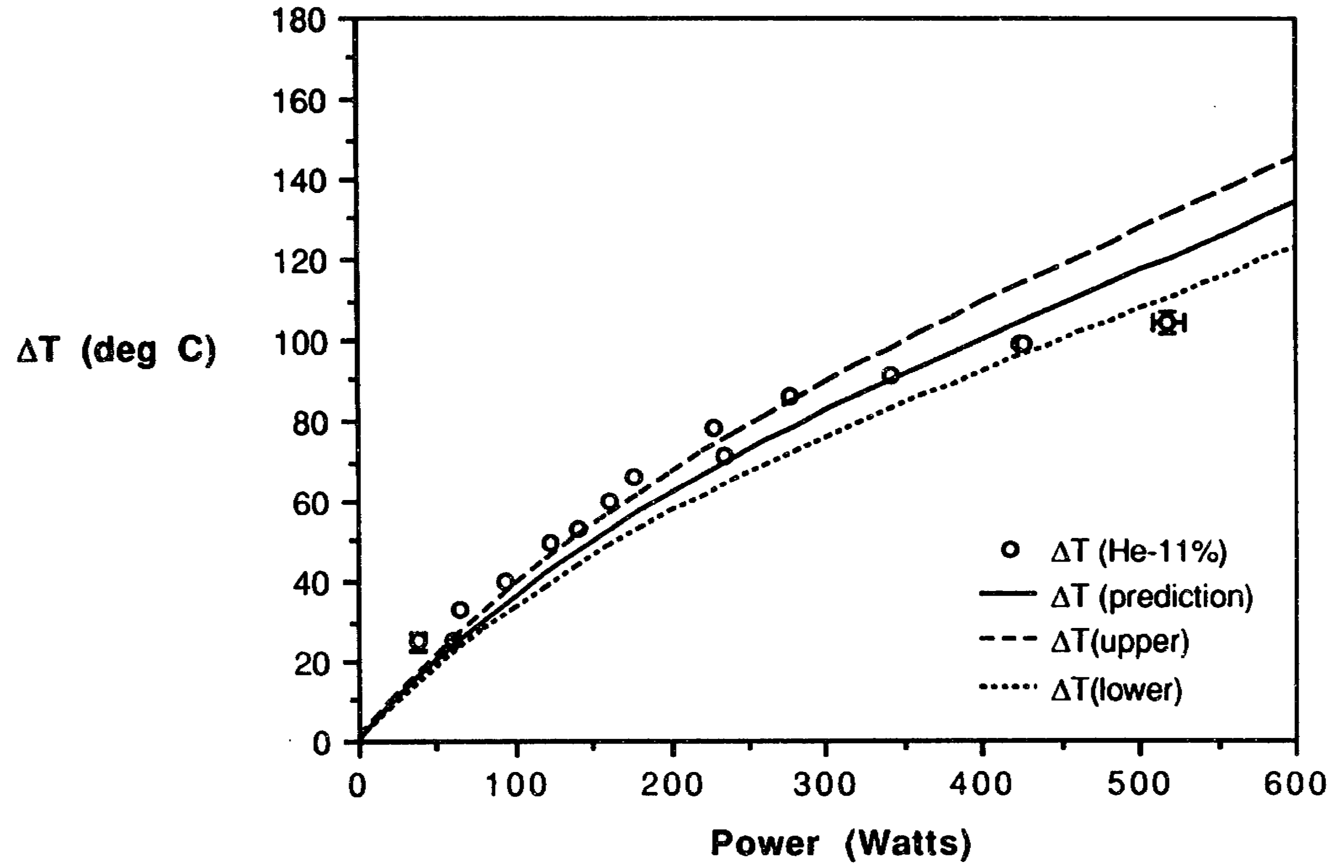

Figure 5-5: Actual and Predicted (with error bounds) ΔT as a function of Power in Pressurized Helium (15 psig)

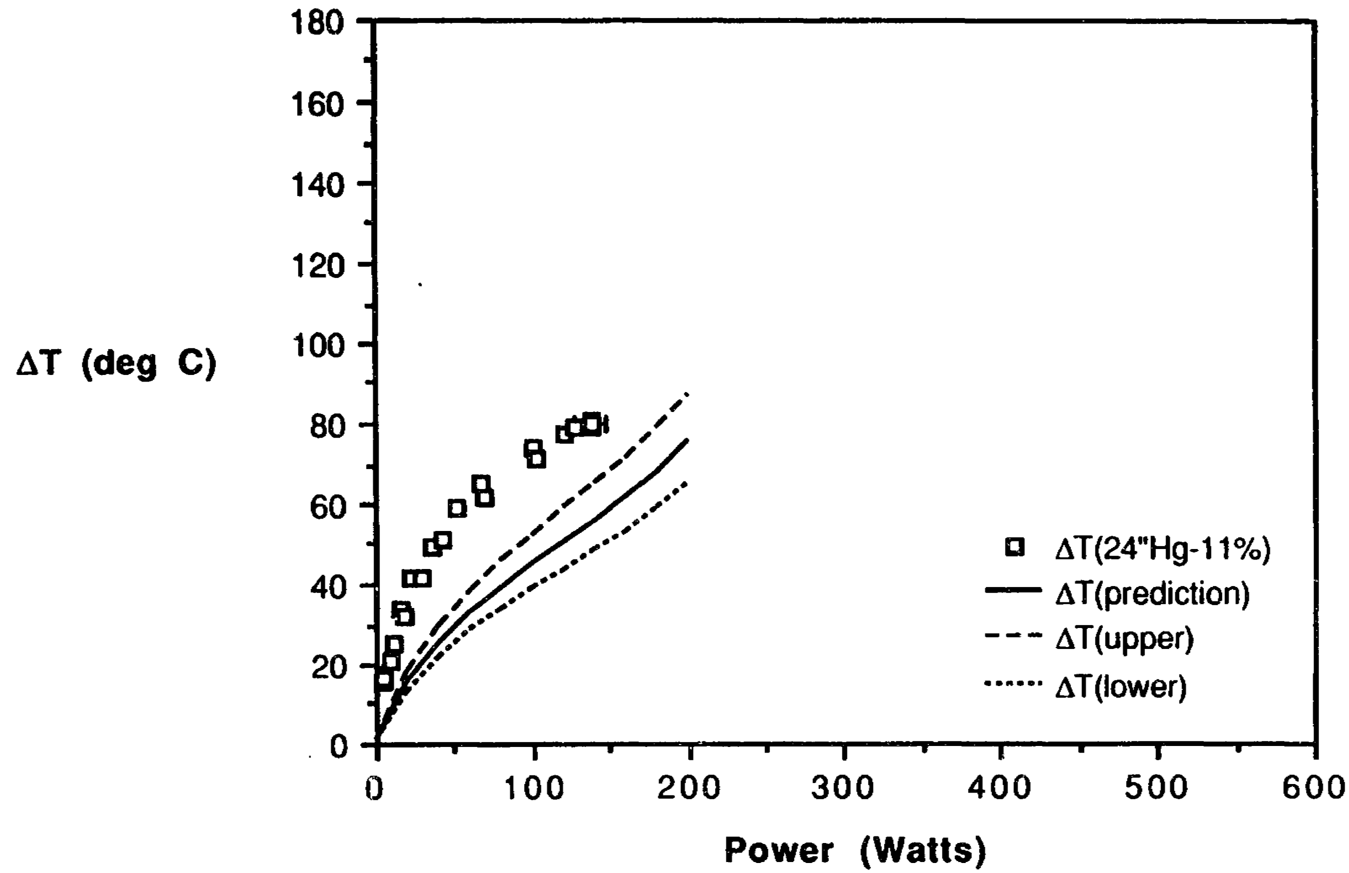

Figure 5-6: Actual and Predicted (with error bounds) ΔT as a function of Power at Below Atmospheric Pressure (24 inches Hg) with Air as the Initial Fill Gas

In general, the predictions agree with the test data obtained from the experimental apparatus. The individual assessments of these comparisons are presented in Section 5.5.

5.5 ASSESSMENT OF COMPARISON

The graphical comparisons of the test data obtained from the experimental apparatus and the predictions from the lumped k_{eff}/h_{edge} model and the Wooten-Epstein relationship are provided in Section 5.4. This section will assess each comparison.

One generic difference between the lumped k_{eff}/h_{edge} model and the test data obtained from the experimental apparatus could possibly be due to the model's assumption that the wall temperature is uniform. This assumption is not correct in the present configuration and operation of the experimental apparatus. The experimental wall temperature's were averaged for input into the lumped k_{eff}/h_{edge} model and the actual difference varied as much as 9.6°C.

The general assessment of the Air/Nitrogen experimental data and predictions, which are graphically shown in Figure 5-3, is that there is good agreement. The shapes of the prediction curves (lumped k_{eff}/h_{edge} and Wooten-Epstein) are similar. The lumped k_{eff}/h_{edge} model prediction is more conservative that the Wooten-Epstein prediction by predicting a higher differential temperature at the same power. The experimental data follows more closely to the Wooten-Epstein prediction; however, the Wooten-Epstein consistently underpredicts the differential temperature. At higher powers, the differential temperature of the experimental data becomes less than the differential temperature of the predictions; however, overall there is good agreement.

The general assessment of the Argon experimental data and prediction and the Helium experimental data and prediction, which are graphically shown in Figures 5-4 and 5-5 respectively, is that there is good agreement. The trends are the same: (1) the lumped k_{eff}/h_{edge} model predictions underpredict the experimental data differential temperatures at low powers and (2) at higher powers (as mentioned earlier with the Air/Nitrogen data), the differential temperatures of the experimental data become less than the differential temperatures of the predictions; however, the crossover point for the predictions are different. The Argon crossover point occurs at approximately 275 Watts, and the Helium crossover point occurs at approximately 350 Watts. Additionally, the Air/Nitrogen crossover point occurs at approximately 150 Watts. The differences between the experimental data and the predictions may be due to the unknown exact value of the Heater Rod surface and Boundary Condition Box interior wall emissivities and the scatter in the average wall temperature. Overall there is good agreement.

The general assessment of the Below Atmospheric Pressure experimental data and prediction, which are graphically shown in Figure 5-6, is that there is not good agreement. The lumped k_{eff}/h_{edge} model prediction underpredicts the experimental data differential temperature. The differences between the experimental data and the prediction may be partially attributed to the unknown exact value of the Heater Rod surface and Boundary Condition Box interior wall emissivities and the scatter in the average wall temperature. The differences may also be attributed to the possibility (1) that the apparatus was operated in the slip regime (29.94 inches Hg $< P <$ 29.90 inches

Hg) instead of in the continuum regime (P > 29.90 inches Hg) or (2) that convective heat transfer plays a more important role than assumed in the lumped k_{eff}/h_{edge} model. These two possibilities have been investigated and are discussed individually.

As discussed in Section 4.2, the experimental apparatus was to be operated at approximately 24 inches Hg to ensure that it remained in the continuum regime shown in Figure 4-1. The pressure of 24 inches Hg was chosen so that instrument error or human error would not be factors. To ensure that the experimental apparatus was operated in the continuum regime, additional data was obtained from the apparatus at various below atmospheric pressures for comparison. Data was acquired with the experimental apparatus at 16 inches Hg and 20 inches Hg, in addition to the standard test pressure of 24 inches Hg, at the same Heater Rod controlling temperature of 240°C without Boundary Condition Box side or end heaters operating. The resulting data sheets are provided in Appendix E.8. The differential temperatures of the experimental data obtained at 24 inches Hg (± 2) were plotted along with the data obtained at 16 inches Hg and at 20 inches Hg. This plot is shown in Figure 5-7. The differential temperature for the three below atmospheric pressures show that all data follow the same trend of being higher than the prediction. Therefore, it was concluded that the experimental apparatus was definitely operated in the continuum region.

The possibility exists that convective heat transfer plays a more important role than that assumed in the formulation of the lumped k_{eff}/h_{edge} model. There are three

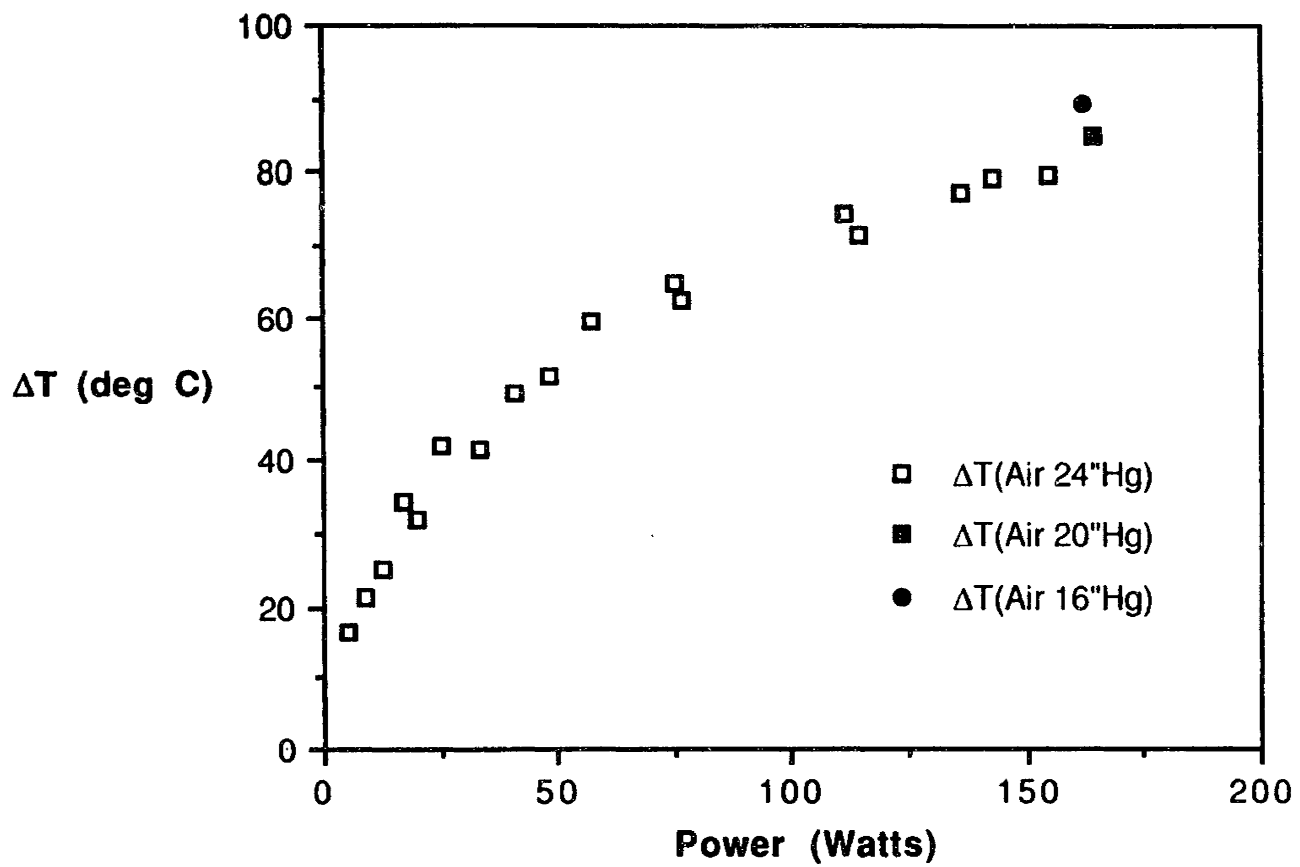

Figure 5-7: Comparison of Differential Temperatures for Below Atmospheric Pressures: 16 inches Hg, 20 inches Hg, and 24 inches Hg

zones of convection in the experimental apparatus: (1) Inside the Boundary Condition Box in the interior Heater Rod region; (2) Inside the Boundary Condition Box between the interior box wall and the Heater Rod region (the edge gap); and (3) Outside the Boundary Condition Box. Each region is discussed individually.

The first zone of convection is inside the Boundary Condition Box in the interior Heater Rod region. The isotherms were examined in the Heater Rod array region for the Below Atmospheric Pressure data (Appendix E.7). Inside the Heater Rod array, the isotherms were almost symmetrical around the centerline point of the array; therefore, convection was not significant inside the array.

The second zone of convection is inside the Boundary Condition Box between the interior box wall and the Heater Rod region (the edge gap). The Boundary Condition Box wall temperatures were examined and compared for the test data obtained at 0 psig and 24 inches Hg. The box wall temperatures at below atmospheric pressure were not symmetrical. For the same power levels, the box wall temperatures at below atmospheric pressure had a similar temperature distribution as the box wall temperatures at atmospheric pressure, i.e., the temperature difference between the Boundary Condition Box top side and bottom side were the same. This temperature distribution indicates that convection could be more significant than assumed in the formulation of the lumped k_{eff}/h_{edge} model for the region between the wall and the first column of heater rods. This could be due to the experimental apparatus having a relatively large rod to wall gap.

The third zone of convection is outside the Boundary Condition Box. The relative importance of convective heat transfer in this zone and in general for data in air at 0 psig and 24 inches Hg is illustrated in Figure 5-8 where the differential temperatures between the wall and its nearest neighboring Heater Rod column are shown for air at 0 psig and 24 inches Hg at similar power levels. This figure demonstrates the importance of convective heat transfer in the second and third zones. For the second zone note that the rod to wall temperature difference for the air data is larger than that for the Below Atmospheric Pressure data, suggesting that convection is more dominant in the former case. For the third zone note that the wall temperature value for the Below Atmospheric Pressure data is much larger than that for the air data. Again this suggests that convection, this time outside the box, is more significant for the air data.

As mentioned in the comparisons between the experimental test data and the predictions obtained in Air/Nitrogen, Argon, and Helium, convective heat transfer is important at larger powers causing the differential temperatures of the experimental data become less than the differential temperatures of the predictions. Convection is not as strong in air at 24 inches Hg; however it is still present. Figure 5-6 shows that the differential temperatures of the experiment are trending toward the differential temperatures of the prediction, and it appears that a crossover point would occur if the experimental apparatus could be operated at high enough powers and temperatures. However, the reason that the differential temperature for the experimental data exceeds the prediction for below atmospheric pressure at low powers remains unexplained.

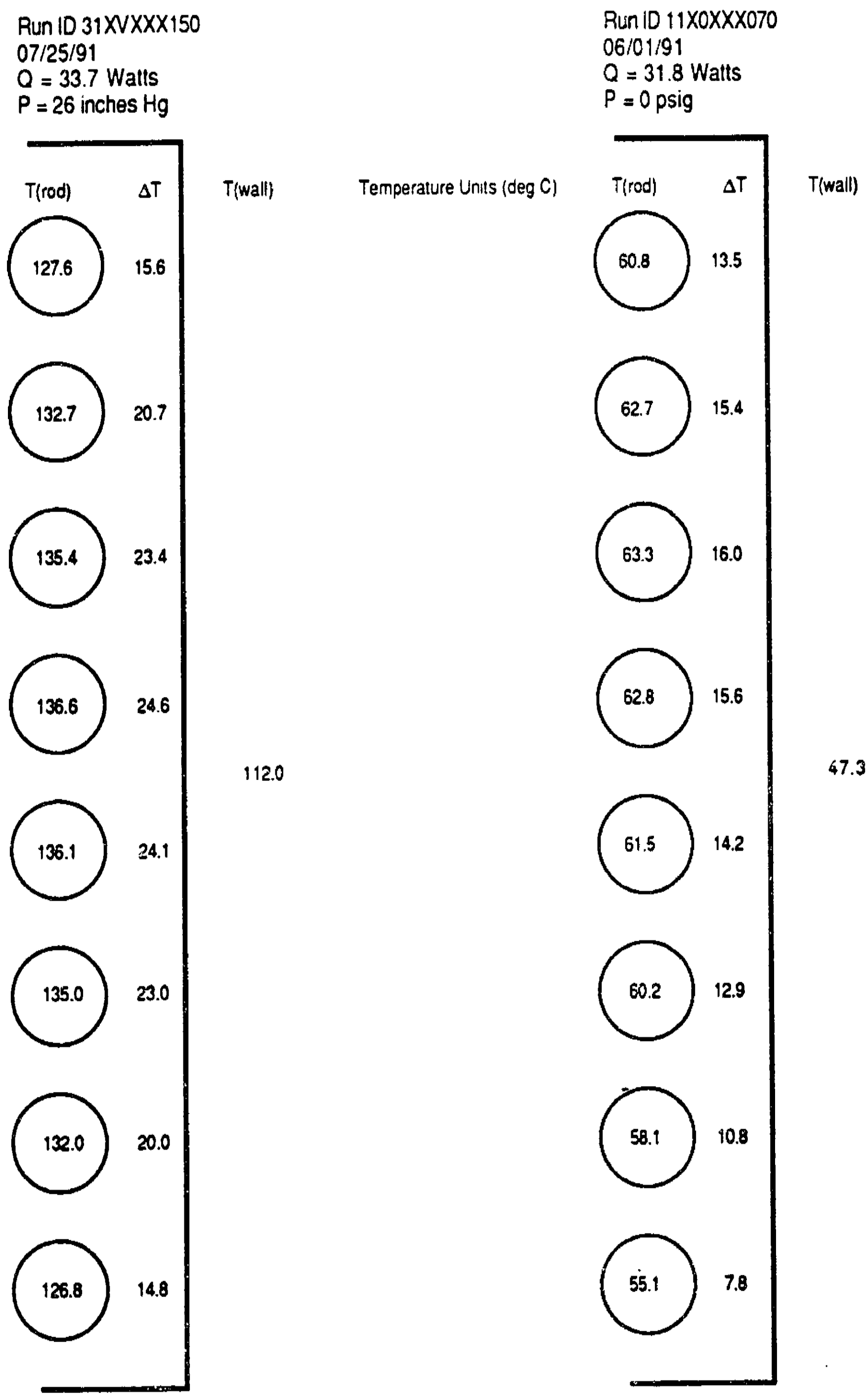

Figure 5-8: Differential Temperature Between the Boundary Condition Box Wall and Its Nearest Neighboring Heater Rod Column for Air at 0 psig and 24 inches Hg at Similar Power Levels (page 1 of 2)

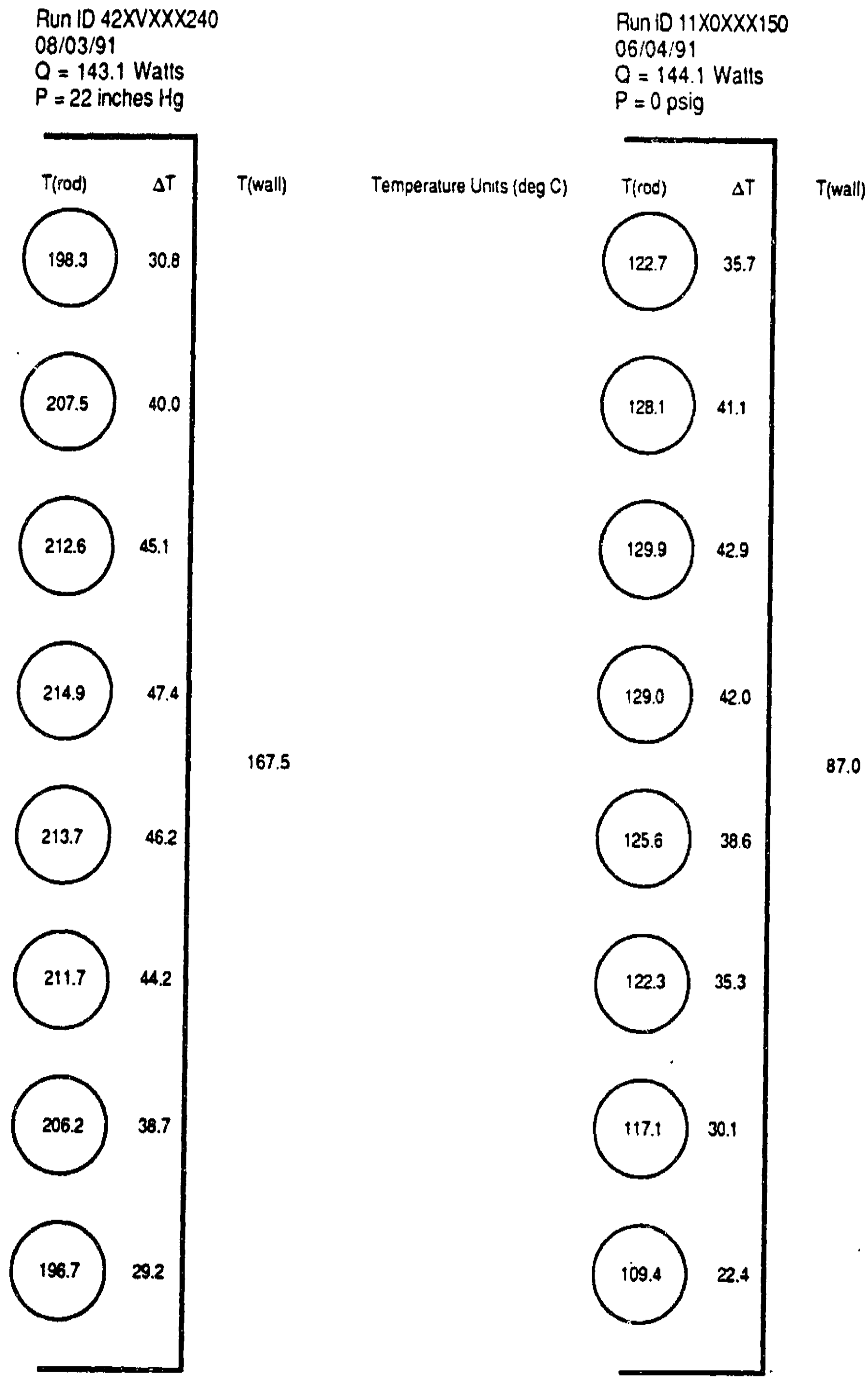

Figure 5-8: Differential Temperature Between the Boundary Condition Box Wall and Its Nearest Neighboring Heater Rod Column for Air at 0 psig and 24 inches Hg at Similar Power Levels (page 2 of 2)

5.6 CHAPTER SUMMARY

The test data obtained from the experimental apparatus is reduced in Chapter 5 using the lumped k_{eff}/h_{edge} model [M-1] and the Wooten-Epstein relationship [B-2]. Chapter 5 also presents an error analysis of the test data. There are two types of error: systematic and random. The systematic error accounts for the end heat losses in the experimental apparatus, and the random error accounts for possible errors in measuring the current, voltage, and temperature in the system.

The corrected test data (after error analysis) and the predictions generated by the lumped k_{eff}/h_{edge} model and the Wooten-Epstein relationship are compared. The comparison shows good agreement between the predictions and the test data in each Test Campaign with the exception of the Below Atmospheric Pressure data, Test Campaign 3 Matrix 1 and Test Campaign 4 Matrix 2.

CHAPTER 6: SUMMARY AND CONCLUSIONS

6.1 SUMMARY

The work on this research project is aimed at formulating a unified overall model of heat transfer in a dry medium. The goal of current research work by Sandia National Laboratories, of which this thesis is a part, is "to develop a fundamental understanding of the heat transfer mechanisms in a dry horizontally-oriented nuclear spent fuel assembly," and to characterize "the magnitude of thermal conductance offered by radiation, conduction, and convection" and the relative importance of each heat transfer mode [S-1]. This thesis work designed and operated an experiment to simulate the heat transfer characteristics of an 8x8 square heater rod array (similar to a Boiling Water Reactor fuel assembly), and recorded the temperatures inside the heater rods at a variety of power levels. The reduced data from this experiment has been utilized to verify a model developed to predict the maximum pin surface temperature in a fuel assembly and to characterize the relevant heat transfer mechanisms in a fuel assembly. This model was developed by R.D. Manteufel in his PhD Thesis at the Massachusetts Institute of Technology, 1991 in related work for this research project [M-1]. R.D. Manteufel's PhD Thesis also contains a complete literature review for experimental and theoretical heat transfer in an enclosed rod array.

Prior to assembly of the experimental apparatus, a Quality Assurance Program was developed at MIT by the author as imposed by Sandia National Laboratories (SNL) in June 1990. The Quality Assurance Program is required to provide a high level of confidence that the experimental system or individual components will be fully useable and referenceable by outside parties. The Program consists of a general guidance MIT NED Quality Assurance Program Plan and implementing procedures, MIT NED Administrative Procedures. The major points of the Program include identification of a Quality Level of Effort, documentation of activities performed, retention of documents, calibration of measuring and test equipment, inspection of activities performed, and certification and training of personnel. These points are discussed in Section 2.2 and further information can be obtained from the latest revision to the MIT NED QA Manual (as of August 9, 1991) provided in Appendix A. The QA Program was audited by a SNL representative in April 1991 and has been deemed effective. The MIT NED QA Program documents are written in a format that can be applied to any experimental research project performed at MIT or any other university.

The conceptual design of each experimental component was chosen to emulate an actual 8x8 Boiling Water Reactor spent fuel assembly and its containment in a transportation cask. The major components of the experiment are the Heater Rods, the Rod Support Plates, the Boundary Condition Box, the Containment Vessel, and the Instrumentation and Control Equipment. Chapter 3 discusses each component in detail and provides the manufacturer's engineering drawings for each.

The Heater Rods are 0.375 inch diameter, 24.5 inch long copper sheathed special order electric-resistance cartridge heaters with a type K thermocouple (Chromel, (+) lead; and Alumel, (-) lead) located at the centerline of the Heater Rod insulated in compacted magnesium oxide [W-2]. The Heater Rods were purchased and received prior to the development and implementation of the MIT NED Quality Assurance Program. The rods had to be individually inspected to ensure acceptability, and the thermocouples had to be calibrated in-house. These Heater Rods are arranged in an 8x8 square array with a rod pitch to diameter ratio of approximately 1.33 using Rod Support Plates located one inch from each end of the Heater Rods.

The Rod Support Plates are two identical special order machined 4.5 inch square 1095 Carbon Steel plates, 0.032 inch thick, with an 8x8 square array of 0.380 inch holes centered on each plate. The resulting 8x8 square array of Heater Rods rests in a Boundary Condition Box.

The Boundary Condition Box provides the boundary condition for the Heater Rod Array with attached heaters for temperature control. The Boundary Condition Box Support Structure is a special order rectangular 6061 Aluminum box, 6.55 inches square outside with a 1.00 inch wall thickness, 4.55 inches square inside, and 25.00 inches in length with 4 type K thermocouples attached to the surface of each box side with high temperature and high thermally conductive epoxy; one positioned 2 inches, two positioned 12.5 inches, and one positioned 23 inches from the end of the box, and one type K thermocouple mechanically attached to the surface of each box side positioned 12.5 inches from the end of the box. The heaters are mechanically attached to the box exterior. The Boundary Condition Box is positioned horizontally and centered in the Containment Vessel.

The Containment Vessel as a special order ASME approved and stamped pressure (75 psig)/full vacuum vessel constructed from 18 inch outside-diameter, 62 inch long SA53-B Carbon Steel pipe with a 0.375 inch wall thickness sealed at each end with 150 pound SA105 Carbon Steel flanges. The vessel has a total of 13-3/4 inch female NPT threaded tap penetrations. Nine of the thirteen penetrations are utilized in the experiment. One penetration is used for the dual pressure safety relief valves; one penetration is used for the compound pressure gauge; one penetration is used for power feedthroughs; five penetrations are used for thermocouple feedthroughs; one penetration is used for the Containment Vessel Pressure System; and one penetration is used for the Containment Vessel Vacuum System. The penetrations are not rated for pressure operation; therefore for safety and legal reasons, the as-built apparatus was limited to pressure operation not to exceed 20 psig.

The experimental apparatus has two types of Instrumentation and Control Systems. These systems are the Data Acquisition System and the Power Systems. As directed by MIT NED Administrative Procedure 2.5, "Control of Measuring and Test Equipment," the instruments used for support of data gathering activities are calibrated utilizing reference standards whose calibration is certified as being traceable to the National Institute of Standards and Technology (NIST).

The Data Acquisition System is comprised of Hewlett Packard components on loan from several research projects at MIT. The Power Systems are split into two separate control systems; one is the Heater Rod System and the other is the Boundary Condition Box System. The Heater Rod System controls and monitors the power delivered to the Heater Rods. The control function is provided by the Electronic Control Systems (ECS) Control/Alarm Model 6400-K-4-1-1-2-1 by controlling the temperature of the Heater Rod in position 4-4. Redundant instrumentation for current, voltage, and power are provided in the Heater Rod System to monitor the power delivered to the Heater Rods. The Boundary Condition Box System controls the power delivered to each box side and end. The control function is provided by individual Omega Model CN9111 and Model CN9111A Microprocessors for the box sides and box ends, respectively.

The assembly of the experimental system is described in detail in Section 3.7. Particular items should be noted. Prior to assembly of the experimental system, each Heater Rod, Rod Support Plate, and the interior wall of the Boundary Condition Box Support Structure were painted black with Krylon High Heat Spray Paint to approximate the emissivity of the system to 0.9. During the thermocouple connection to the Data Acquisition System multiplexers care and caution was taken to ensure that the multiplexer channel assigned to a particular thermocouple indeed was that particular thermocouple. This was accomplished by two individuals handling one thermocouple at a time inside and outside the containment vessel using a multimeter to verify continuity.

The experimental apparatus was operated under four major Test Campaigns where the parameters of the apparatus: the power input to the Heater Rod System, the controlling temperatures of the Boundary Condition Box System, the heat transfer medium in the Containment Vessel, and the operating pressure of the heat transfer medium, were varied to enhance or eliminate each of the heat transfer mechanisms.

Test Campaign 1 Matrix 1 was performed at atmospheric pressure in air at 14 Heater Rod power levels with the controlling temperature ranging from 40°C to 250°C without the Boundary Condition Box side or end heaters operating and 10 Heater Rod power levels with the controlling temperature ranging from 70°C to 250°C with the Boundary Condition Box end heaters operating. The data acquisition in Test Campaign 1 Matrix 1 prior to May 7, 1991 is the Debugging Phase. This Phase is discussed in Section 4.5. The purpose of Test Campaign 1 Matrix 1 is to produce a base set of data.

Test Campaign 2 Matrix 1 was performed at above atmospheric pressure (15 ± 3 psig) in three different heat transfer mediums (Nitrogen, Argon, and Helium) at 9 Heater Rod power levels with the controlling temperature ranging from 70°C to 250°C without the Boundary Condition Box side or end heaters operating. The purpose of Test

Campaign 2 Matrix 1 is to produce a set of data that accentuates conduction with Helium and accentuates convection with Argon and increased pressure.

Test Campaign 3 Matrix 1 was performed at below atmospheric pressure (24 ± 2 inches Hg) in air at 9 Heater Rod power levels with the controlling temperature ranging from 70°C to 250°C without the Boundary Condition Box side or end heaters operating. The purpose of Test Campaign 3 Matrix 1 is to produce a set of data that minimizes convection.

Test Campaign 4 identified, after testing had begun, additional tests that should be performed. Test Campaign 4 Matrix 1 expanded upon Test Campaign 2 Matrix 1 with above atmospheric pressure testing in the three heat transfer mediums with 6 additional Heater Rod power levels with a controlling temperature ranging from 70°C to 240°C. Test Campaign 4 Matrix 2 expanded upon Test Campaign 3 Matrix 1 with below atmospheric pressure testing in air with 5 additional Heater Rod power levels with a controlling temperature ranging from 140°C to 240°C.

The test data showed that each heat transfer mechanism could be enhanced by varying the operating parameters of the experimental apparatus. The complete set of test data is provided in Appendix E.

The test data is reduced in Chapter 5 using the lumped k_{eff}/h_{edge} model developed by R.D. Manteufel in his Doctoral Thesis at MIT in related work on this research project [M-1] and the Wooten-Epstein relationship developed at Battelle Memorial Institute in 1963 [B-2]. An error bound was determined for the lumped k_{eff}/h_{edge} model prediction. This error bound accounts for the unknown exact value of the Heater Rod surface and Boundary Condition Box interior wall emissivities and the scatter in the Boundary Condition Box's average wall temperature.

An error analysis of the test data is performed in Chapter 5. There are two types of error: systematic and random. The systematic error accounts for the end heat losses in the experimental apparatus. A code is used which takes the temperature differential between four heater rod centerline thermocouples with their non-lead end attached thermocouples and weights their loss by the number of heater rods in their corresponding ring to determine the systematic error. The random error accounts for possible errors in measuring the current, voltage, and temperature in the system. The random error is generated by the standard deviation of the measurements.

The corrected test data (after the error analysis) and the predictions generated by from the lumped k_{eff}/h_{edge} model and the Wooten-Epstein relationship are compared in Chapter 5. The comparison shows good agreement between the predictions and the test data in each Test Campaign with the exception of the Below Atmospheric Pressure data, Test Campaign 3 Matrix 1 and Test Campaign 4 Matrix 2.

6.2 CONCLUSIONS

The work on this research project is aimed at formulating a unified overall model of heat transfer in a dry medium. This thesis work designed and operated an experiment to simulate the heat transfer characteristics of an 8x8 square heater rod array (similar to a Boiling Water Reactor fuel assembly), and recorded the temperatures inside the heater rods at a variety of power levels. The reduced data from this experiment has been utilized to verify a model developed by R.D. Manteufel in related work on this research project [M-1] to predict the maximum pin surface temperature in a fuel assembly and to characterize the relevant heat transfer mechanisms in a fuel assembly. There are several major conclusions concerning this research work:

(1) The as-built experimental apparatus accurately simulates the heat transfer mechanisms in a horizontally configured spent nuclear fuel assembly.

(2) A Quality Assurance Program is necessary to provide a high level of confidence that the experimental results obtained from the research project will be fully useable and referenceable by outside parties.

(3) The Test Campaigns performed in the experimental apparatus provide a good base set of test data which can be used to determine the importance of each heat transfer mechanism and to determine what further testing

should be performed to further understand each heat transfer mechanism.

(4) In general, the lumped k_{eff}/h_{edge} model showed good agreement with the experimental results.

6.3 RECOMMENDATIONS FOR FUTURE WORK

This theoretical and experimental research work presents many opportunities for further research in the area of determining the relative importance of radiation, conduction, and convection in a dry horizontally-oriented nuclear spent fuel assembly. The recommendations for future work include the following:

(1) Perform a study to determine additional Test Campaigns necessary to further demonstrate the heat transfer mechanisms, and perform these Test Campaigns under the specified controlled conditions using the experimental apparatus.

(2) Upgrade the as-built Experimental Apparatus with the following modifications:

(a) Future purchases of Heater Rods should specify:

- a rating of 120 Volts/600 Watts to increase the flexibility when electrically configuring the Heater Rod array,
- a new wall thickness of 0.025 inch for more durable Heater Rods, and
- dual internally installed thermocouples calibrated to NIST standards at the centerline and non-lead end of the rod for

a certified multidimensional apparatus.

(b) Containment Vessel power penetrations and thermocouple penetrations that are rated for pressure and vacuum operation should be purchased and installed. These new penetrations would significantly increase the band of testing that could be performed on the experimental apparatus and the overall safety of the experiment.

(c) Boundary Condition Box Support Structure thermocouples should be embedded in the structure wall to provide a more accurate measurement of the wall temperature.

(3) Design and install a Cooling System in the experimental apparatus to allow precise control of the Boundary Condition Box wall temperatures below the natural equilibrium level that they heat up to under non-controlled operation.

(4) Apply the MIT NED Quality Assurance Program developed in this research work to other experimental research projects at MIT and other universities to provide a high level of confidence that the experimental results from the research project will be fully useable and referenceable by

outside parties.

(5) Modify the lumped k_{eff}/h_{edge} model to account for varying the pressure of the heat transfer medium and to refine the assessment of the effects of natural convection heat transfer (i.e., incorporate pressure dependence and natural convection dependence into the model).

(6) Incorporate the ability to calculate standard deviations of the measured power, current, voltage, and temperature into future data acquisition programs.

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APPENDIX A

MIT NED QUALITY ASSURANCE MANUAL

This appendix contains the latest revision of the MIT Nuclear Engineering Department (NED) Quality Assurance Manual with latest revisions issued July 31, 1991. The MIT NED QA Manual contains the most recent revisions of the MIT NED Quality Assurance Program Plan (QAPP) and the MIT NED Administrative Procedures (APs).

Massachusetts Institute of Technology

Nuclear Engineering Department

Experimental Heat Transfer

Quality Assurance Program Plan

May 28, 1991

Revision C

Written by:	Phyllis M. Lovett Research Assistant	05-28-91 Date
Reviewed by:	Randall D. Manteufel Research Assistant	5-28-91 Date
Approved by:	Neil E. Todreas Professor, Nuclear Engineering	5-28-91 Date

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POLICY STATEMENT

It is the policy for the Massachusetts Institute of Technology's (MIT) Nuclear Engineering Department (NED) Contract No. 42-5638, Cavity Heat Transfer, that all functions, services, hardware, and operating systems required to support our scientific and technological objective shall be performed, produced, operated or maintained at quality levels appropriate to the contract objectives. To this end, a Quality Assurance Program with implementing procedures will be established.

It is incumbent upon all project personnel to be familiar with this program and its implementing procedures. Enforcement of this policy is the responsibility of all personnel involved in this project.

PURPOSE AND SCOPE

The purpose of this document is to set forth a Quality Assurance (QA) Program for the Massachusetts Institute of Technology's (MIT) Nuclear Engineering Department (NED) Contract No. 42-5638, Cavity Heat Transfer. This Program will satisfy the requirement imposed by the contractor, Sandia National Laboratories (SNL), in June 1990. The requirement was imposed by SNL to satisfy their Cask Systems Development Program (CSDP) Quality Assurance Program Plan (QAPP). Their Plan states the ultimate objective:

> "The objective of the Department of Energy's (DOE) Office of Civilian Radioactive Waste Management (OCRWM) Cask Systems Development Program is to design, develop, fabricate, test, and certify a family of prototypical casks to be used to transport spent nuclear fuel and high-level radioactive waste to Federal facilities in a national system for disposal of such waste in accordance with the Nuclear Waste Policy Act. Prototype casks will be designed to minimize life cycle costs and fabricated and tested to ensure acceptability for the eventual cask fleet."

The goal of this Program is to sustain a high level of quality in order to provide SNL with a fully useable and referenceable product, to protect the health and safety of workers and the public, and to protect the environment.

This Program has been prepared to be in compliance with the MIT Policies, SNL CSDP QAPP and ANSI/ASME NQA-1-1987 Chapter II QA Basic Requirements and to closely emulate the SNL CSDP QAPP. The MIT Plasma Fusion Center Alcator C-MOD QA Program, dated July 31, 1987, provided additional guidance when preparing this Program.

Abbreviations used in this Program are defined in Appendix A. Terms and definitions are provided in Appendix B.

EXPERIMENTAL QUALITY ASSURANCE PROGRAM PLAN

1.0 ORGANIZATION

1.1 This section defines the organizational structure, responsibilities, and levels of authority within the MIT NED QAPP.

1.2 MIT NED serves as the responsible subcontractor to develop a technical understanding of the heat transfer mechanisms in a horizontally positioned spent fuel assembly for SNL as defined in MIT Contract No. 42-5638.

1.3 The MIT Principle Investigator (PI) is responsible for implementing all aspects of this QAPP and has the authority to resolve disputes involving quality. (Ref. AP-1.4)

1.4 The MIT QA Coordinator is responsible for establishing and implementing the MIT NED QAPP. The MIT QA Coordinator shall review the MIT NED QAPP annually to assess its adequacy and effectiveness and revise the QAPP as necessary. The MIT QA Coordinator has the authority and sufficient organizational freedom to identify problems; to initiate, and recommend solutions to those problems; to verify solutions; and to assure that further processing, delivery, installation, or use is controlled until proper disposition of a nonconformance, deficiency, or unsatisfactory condition has occurred. In addition, the MIT QA Coordinator has the authority to initiate the stoppage of unsatisfactory work. The MIT QA Coordinator acts independently of cost and schedule considerations. (Ref APs 1.1, 1.4, 5.2, 5.3, 5.4)

1.5 Designated Graduate Research Assistants (RAs) have overall responsibility to develop, plan, coordinate, implement, and oversee a broad range of activities as designated by the MIT PI. (Ref. AP-1.4)

1.6 Quality requirements are achieved and maintained by those who have been assigned the responsibility for performing the work. Conformance to established requirements is verified by the MIT QA Coordinator. (Ref. APs 1.4, 4.1, 5.5, 5.7)

1.7 MIT NED Administrative Procedures (APs) are procedures which establish and define the responsibilities, authorities, and interfaces of MIT NED personnel. These interfaces include both internal interfaces within MIT and external interfaces with organizations such as subcontractors. APs also describe the documentation to be completed and retained by MIT NED personnel as a QA record.

2.0 QUALITY ASSURANCE PROGRAM

2.1 This QAPP is formatted to the quality criteria of SNL CSDP QAPP.

2.2 MIT NED has adopted a QA system to assure application of the appropriate level of QA for various tasks. These levels are designated Quality Level 1, 2, and 3. MIT NED AP-5.6 describes the method for determining the Quality Levels and for selecting the appropriate controls for tasks with different impact-of-failure levels.

2.3 The MIT QA Coordinator is responsible for assigning each task a Quality Level and documents the assigned Quality Level on all appropriate project documents (e.g., project QA plans, test procedures, procurement documents). (Ref. AP-5.6)

2.4 The MIT NED QA Program is subject to audit and review by SNL at any reasonable time during MIT's participation under SNL-MIT Contract 42-5638. (Ref. AP-5.3)

2.5 This MIT NED QAPP requires training and indoctrination in the QA Program. Personnel to be indoctrinated or trained shall be identified in this QAPP or in APs. This training is conducted by the MIT QA Coordinator and consists of:

* General QA training including applicable codes, standards, and procedures; applicable QA Program elements; and job responsibilities and authority relating to QA

* Individual meetings with new hires (permanent and part-time) to familiarize them with this QAPP

* Periodic issuance of QA Bulletins to personnel to announce either changes in the QAPP and APs or problems that arise due to noncompliance with the QAPP or APs.

Records of the implementation of indoctrination and training (attendance sheets, training logs, or personnel training records) shall be a QA record. (Ref. APs 1.1, 1.4, 3.3, 3.4, 4.1)

2.6 The MIT PI shall continuously assess the effectiveness of plans and activities to achieve and assure quality. (Ref. AP-1.4)

2.7 Written procedures shall be established for the qualification of inspection, test, and audit personnel to assure that only those personnel who meet the requirements of this QAPP or APs are permitted to perform inspection, test, or audit activities. (Ref. APs 5.5, 5.7)

2.8 Inspection, test and audit personnel qualifications shall be certified in writing in an appropriate form. Certification form will include:

(a) Activities that the personnel are certified to perform

(b) Basis used for certification, which includes such factors as:

(1) Education, experience, indoctrination, and training

(2) Test results, where applicable

(3) Results of capability demonstration

(c) Results of periodic evaluation

(d) Certifier's signature

(e) Date of certification and date of certification expiration.

(Ref. APs 2.10, 4.1, 5.5, 5.7)

2.9 MIT NED AP-5.4 provides for the stoppage of work when conditions warrant. A Stop Work Request may be requested by any personnel but approved only by the MIT PI.

3.0 DESIGN CONTROL

3.1 Design Control requirements are not applicable to MIT NED QAPP. The basis for this has been determined from the SNL CSDP QAPP which states:

> "Per direction, Design Control requirements of DOE/ID10178, Rev. 1, Quality Management Plan for the CSDP are not applicable to SNL's CSDP activities."

4.0 PROCUREMENT DOCUMENT CONTROL

4.1 The originator (requestor) of a purchase requisition (PR) assures that the appropriate technical and quality requirements are included in the PR commensurate with the scope, complexity, importance and degree of risk of a particular material, equipment or service. (Ref. AP-3.2)

4.2 The MIT PI reviews the PR for accuracy and adequacy. (Ref. AP-3.2)

4.3 The MIT QA Coordinator reviews the PR for quality requirements. This review may be waived for off-the-shelf (catalogue) items for which there are no modifications that impact quality, or no appropriate QA requirements. (Ref. AP-3.2)

4.4 Instructions for preparing and processing PRs and Change Requests are found in MIT NED AP-3.2.

4.5 Changes to PRs (Change Requests) are subject to the same review and approval requirements as the original PR. (Ref. AP-3.2)

5.0 INSTRUCTIONS, PROCEDURES, AND DRAWINGS

5.1 Instructions, procedures, and drawings will be clear, complete, approved documents. These documents provide specific details for implementing the requirements of the QAPP and include or reference appropriate quantitative or qualitative acceptance criteria. (Ref. APs 1.1, 2.7, 3.3)

5.2 Procedures generated by MIT NED are of two basic types: administrative procedures (APs) and detailed test procedures (TPs). APs govern the processes of planning, management controls, and quality verification. TPs prescribe the detailed actions required to achieve quality in performing testing activities. Organizational responsibilities, authorities, and interfaces for approval of test procedures are defined in this QAPP, Section 11, Test Control. (Ref. APs 1.1, 2.7)

6.0 DOCUMENT CONTROL

6.1 The document control system shall be documented and shall provide for the:

(a) identification of documents to be controlled and their specified distribution

(b) identification of assignment of responsibility for preparing, review, approving, and issuing documents

(c) review of documents for adequacy, completeness, and correctness prior to approval and issuance.

(Ref. AP-3.3)

6.2 Controlled documents, i.e., those used to accomplish and/or verify quality-related activities, include such documents as this QAPP, APs, Project Test Procedures, and Engineering Drawings. (Ref. AP-3.3)

6.3 The MIT NED QAPP and MIT NED APs are distributed to the MIT PI, MIT QA Coordinator, and RAs. (Ref. AP-3.3)

6.4 Project test activities are performed using approved test procedures. The process of making major and minor modifications to test procedures is described in MIT NED AP-1.1. (Ref. AP-2.7)

6.5 Minor changes to controlled documents such as inconsequential editorial corrections, shall not require the same review and approval as the original. Changes to documents, other than minor, shall be considered major changes and require the same review and approval as the original. (Ref. AP-1.1)

6.6 Minor or major changes to controlled documents are distributed to all controlled document holders. (Ref. APs 1.1, 3.3)

7.0 CONTROL OF PURCHASED ITEMS AND SERVICES

7.1 The MIT NED QA Program shall ensure that purchased material, equipment, and services conform to the procurement documents. These measures include, as appropriate, source evaluation and selection, source inspections, audits, receipt inspection and acceptance testing, of products upon delivery. (Ref. AP-3.2)

7.2 The inspection report will confirm that material and equipment conform to the procurement requirements required for acceptance of the product. (Ref. AP-2.10)

7.3 The MIT NED QA Program includes provisions for the procurement and use of off-the-shelf items and materials. (Ref. AP-3.2)

8.0 IDENTIFICATION AND CONTROL OF ITEMS

8.1 Identification and Control of Items not acceptable for use shall be indicated through the use of tags to prevent inadvertent use or installation. (Ref. AP-2.9)

8.2 Identification and control of major equipment will be in accordance with MIT Policy. (Ref. AP-2.9)

9.0 CONTROL OF PROCESSES

9.1 Requirements for control of processes affecting quality of items and services include special processes that control or verify quality (including welding). (Ref. APs 1.1, 2.7, 2.8)

9.2 The following controls are imposed on special processes affecting the quality of a project activity:

* Individuals performing a special process are qualified by training and/or experience commensurate with the scope, complexity, or special nature of the process in accordance with applicable codes, standards, or specifications.

* Equipment used for special processes is evaluated for its suitability for the intended application.

* Procedures for defining and controlling special processes are written by qualified personnel who are familiar with the special processes. These procedures include or reference procedures, personnel and equipment qualification requirements, and include the requirements of applicable codes and standards, including acceptance criteria.

(Ref. APs 1.1, 2.7, 2.8, 4.1, 5.7)

9.3 For personnel performing special processes, measures shall be established for obtaining proof of their certification to perform the process, the period the certification remains in effect, and the conditions under which recertification would be required. (Ref. AP-5.7)

10.0 INSPECTION

10.1 The MIT QA Coordinator determines the need for inspectors, and upon approval, the MIT PI provides for them. Inspections are performed as specified by the originator of a Purchase Requisition (PR) in accordance with approved procedures. (Ref. APs 2.10, 3.2)

10.2 Inspection activities shall be planned and documented to identify characteristics, methods, acceptance criteria, and inspection results. A record of inspection activity shall be maintained as QA record. (Ref. APs 2.10, 3.4)

10.3 Personnel performing inspections shall be qualified based on their abilities gained through education, training, and experience. (Ref. AP-5.7)

11.0 TEST CONTROL

11.1 Tests required for the collection of data shall be controlled, planned, executed, documented, and evaluated. (Ref. AP-2.7)

11.2 Personnel performing testing activities shall be qualified based on their abilities gained through education, training, and experience. (Ref. AP-5.7)

11.3 Test activities are conducted to documented and approved test procedures. The RA prepares test procedures to assure compliance with experiment/investigation requirements or other applicable criteria. Test procedures include data sheets for data accumulation. (Ref. AP-2.7)

11.4 In lieu of procedures, appropriate sections of related documents such as ASTM methods, supplier manuals, equipment maintenance instructions, or approved drawings may be used provided acceptance criteria and adequate instructions to assure the required quality of work are provided. (Ref. AP-2.7)

12.0 CONTROL OF MEASURING AND TEST EQUIPMENT

12.1 Measuring and Test equipment shall be calibrated and this calibration shall be directly traceable to the National Institute of Standards and Technology (NIST) primary standards. A list of each calibrated item, the calibration interval, item identification number, and other pertinent data shall be maintained as a QA record. (Ref. APs 2.8, 3.4)

12.2 If an instrument is reported as being out of calibration, the project test personnel (in consultation with the MIT PI) review the as-found calibration data to determine the effect of the out-of-calibration instrument on the test data. If the data are acceptable, the project test personnel and MIT PI sign or initial the calibration sheet to indicate acceptance, and keep the calibration sheet for QA record retention. If the MIT PI determines that the data are questionable or unacceptable, a nonconformance report (NCR) is initiated in accordance with approved procedures. (Ref. AP-5.8)

13.0 HANDLING, STORAGE, AND SHIPPING OF ITEMS

13.1 Items shall be suitably stored to protect against deterioration or damage. Items with any special controls or environments shall be labeled appropriately. (Ref. AP-2.9)

14.0 INSPECTION, TEST, AND OPERATING STATUS

14.1 The status of inspection and component testing activities shall be identified either on the items or in documents traceable to the items where it is necessary to assure that required inspections and component tests are performed and to assure that items which have not passed the required inspections and component tests are not inadvertently installed, used, or operated. (Ref. APs 2.7, 2.10)

14.2 As necessary, the inspection, test, and operating status of individual items shall be controlled by calibration stickers, tags, markings, and notations in a notebook to ensure that required inspections and tests are performed in the proper sequence. The MIT QA Coordinator has the authority for application and removal of stickers, tags, or markings. (Ref. APs 2.7, 2.8, 2.10)

14.3 Status indicators shall be used to indicate the operating status of items, systems, and component, such as by tagging valves and switches, to prevent inadvertent operations. (Ref. APs 2.7, 2.8, 2.10)

15.0 CONTROL OF NONCONFORMING ITEMS

15.1 Any item or sample that does not conform to specified requirements or procedures is considered a nonconformance and requires a Nonconformance Report (NCR) to be issued in accordance with MIT NED AP-5.8.

15.2 Items found nonconforming will be tagged with a nonconformance hold tag or segregated to prevent inadvertent use. (Ref. AP-5.8)

15.3 The MIT PI shall approve any NCR dispositioned use-as-is, repair, and conditional use. (Ref. AP-5.8)

16.0 CORRECTIVE ACTION

16.1 Measures will be established to identify and promptly correct conditions adverse to quality. (Ref. AP-5.2)

16.2 Significant conditions judged adverse to quality such as failures, malfunctions, and deficiencies shall be promptly identified, the cause determined, and corrective actions taken to correct the adverse condition and to preclude repetition. In accordance with MIT NED AP-5.2, the MIT QA Coordinator shall take appropriate action to assure:

* Prompt initiation of corrective action to preclude recurrence
* Verification of proper implementation by follow-up reviews
* Submission of a report documenting the deficiency, its cause, and corrective action taken.

17.0 QUALITY ASSURANCE RECORDS

17.1 A records management program shall be implemented to assure the generation, review, approval, authentication, protection, storage, and retrieval of QA records. (Ref. AP-3.4)

17.2 QA records shall be under the custodial care of the MIT QA Coordinator. (Ref. APs 1.4, 3.4)

17.3 QA records furnish documentary evidence of compliance with applicable codes, standards, drawings, test procedures, and specifications for items, services, or activities that affect quality. (Ref. AP-3.4)

17.4 QA records are defined in this QAPP and MIT NED AP-3.4.

17.5 Records of the methods and procedures used to obtain technically significant data will be maintained as QA records, which may include both documents and physical samples, to furnish historical evidence for future evaluation. (Ref. AP-3.4)

18.0 AUDITS

18.1 Internal project audits are conducted to verify compliance with all aspects of the QA program and to determine the QA program's effectiveness. The MIT QA Coordinator ensures these audits are conducted in accordance with an audit plan, and written procedures or checklists. Audit results are documented and reported to the MIT PI. Conditions requiring prompt corrective action are reported immediately. (Ref. AP-5.3)

18.2 The MIT QA Coordinator shall develop and document an audit plan for each audit. (Ref. AP-5.3)

18.3 The MIT QA Coordinator shall be qualified and certified to perform audits in accordance with procedures. (Ref. AP-5.5)

18.4 The MIT QA Coordinator shall issue an audit report for each audit. The MIT QA Coordinator shall assure that the audited organization investigate adverse audit findings, schedule corrective action including measures to prevent recurrence, and notify the MIT QA Coordinator in writing of action taken or planned. The MIT QA Coordinator shall review the audit responses for adequacy and resolve any concerns. The MIT QA Coordinator shall assure that follow-up action is taken to verify that corrective action was accomplished as scheduled. (Ref. APs 5.2, 5.3)

APPENDIX A

ABBREVIATIONS

ANSI	-	American National Standards Institute
AP	-	Administrative Procedure
ASME	-	American Society of Mechanical Engineers
CSDP	-	Cask Systems Development Program
DOE	-	Department of Energy
MIT	-	Massachusetts Institute of Technology
NCR	-	Nonconformance Report
NED	-	Nuclear Engineering Department
NIST	-	National Institute of Standards and Technology
OCRWM	-	Office of Civilian Radioactive Waste Management
PI	-	Principle Investigator
PR	-	Purchase Requisition
QA	-	Quality Assurance
QAPP	-	Quality Assurance Program Plan
SNL	-	Sandia National Laboratories
TP	-	Test Procedure
TSDD	-	Transportation System Development Department

APPENDIX B

TERMS AND DEFINITIONS

1. **GENERAL**

This Appendix contains definitions of words used in this document, and these definitions are identical to the ones given in the SNL CSDP QAPP.

2. **TERMS AND DEFINITIONS**

Acceptance Criteria. Specified limits placed on characteristics of an item, process, or service defined in codes, standards, or other requirement documents.

Audit. A planned and documented audit activity performed to determine by investigation, examination, or evaluation of objective evidence the adequacy of and compliance with established procedures, instructions, drawings, and other applicable documents, and the effectiveness of implementation. An audit should not be confused with inspection activities performed for the sole purpose of process control or product acceptance.

Certification. The act of determining, verifying, and attesting in writing to the qualifications of personnel, processes, procedures, or items in accordance with specified requirements.

Corrective Action. Measures taken to rectify conditions adverse to quality and, where necessary, to preclude repetition.

Document. Any written or pictorial information describing, defining, specifying, reporting, or certifying activities, requirements, procedures, or results.

Document Control. The activity of assuring that documents are reviewed for adequacy, approved for release by authorized personnel, and distributed to and used at the location where the prescribed activity is performed.

Inspector. A person who performs inspection activities to verify conformance to specific requirements.

Inspection. Examination or measurement to verify whether an item or activity conforms to specified requirements.

Item. An all-inclusive term used in place of any of the following: appurtenance, assembly, component, equipment, material, module, part, structure, subassembly, subsystem, system, or unit.

Measuring and Test Equipment (M&TE). Devices or systems used to calibrate, measure, gage, test, or inspect in order to control or acquire data to verify conformance to specified requirements.

Nonconformance. A deficiency in characteristic, documentation, or procedure that renders the quality of an item or activity unacceptable or indeterminate.

Procedure. A document that specifies or describes how any activity is to be performed.

Procurement Document. Purchase requisitions, purchase orders, drawings, contracts, specifications, or instructions used to define requirements for purchase.

Purchaser. The organization responsible for establishment of procurement requirements and for issuance, administration, or both, of procurement documents.

Qualification (Personnel). The characteristics or abilities gained through education, training, or experience, as measured against established requirements, such as standards or tests, that qualify an individual to perform a required function.

Quality Assurance (QA). All those planned and systematic actions necessary to provide adequate confidence that a structure, system, or component will perform satisfactorily in service.

Quality Assurance Record. An individual document or other item that has been executed, completed, and approved and that furnishes evidence of the quality and completeness of data (including raw data), items, and activities affecting quality; documents prepared and maintained to demonstrate implementation of quality assurance programs (e.g., audit, inspection reports); procurement documents; other documents such as plans, correspondence, documentation of telephone conversations, specification, technical data books, papers, photographs, and data sheets; and items such as magnetic media, physical samples; and other materials that provide data and document quality regardless of physical form or characteristic. A completed record is a document or item (and documentation) which will receive no more entries, whose revisions would normally consist of a reissue of the document (or documentation), and that is signed and dated by the originator and, as applicable, by approval personnel.

Quality Level 1 (QL1). Items or activities assigned this classification are ones where an omission, error, or failure could directly impact public radiological health and safety. From a mechanistic perspective, if an adverse radiological effect (exceeding regulatory limits) may be initiated by an omission, error, or failure of an item or activity, then that item or activity must be classified as QL1. The determination of which initiating events involving items and activities that might result in the above effects must be made on a case-by-case basis at the time of classification. Criticality events and failure of containment and shielding are among the events that require analysis. QL1 items and activities shall meet the basic and supplemental requirements of ANSI/ASME NQA-1.

Quality Level 2 (QL2). Items and activities assigned this classification are ones, under the direct control of the OCRWM CSDP, where an omission, error, or failure could lead to circumstances that could require QL1 items or activities to perform their safety-related function. Therefore, an indirect relationship exists between QL2 items and activities and adverse radiological effects to public health and safety. QL2 items and activities shall meet the basic and selected supplemental requirements of ANSI/ASME NQA-1.

Quality Level 3 (QL3). QL3 is for assignment to OCRWM activities selectively chosen because of special programmatic importance other than radiological safety. These include mission-oriented activities controlled by DOE Orders and procedures which reflect good technical management practices for the assurance of Quality. Additionally, NQA-1 requirements may be selectively applied as determined by line management.

Receiving. Taking delivery of an item at a designated location.

Repair. The process of restoring a nonconforming characteristic to a condition such that the capability of an item to function reliably and safely is unimpaired, even though that item still does not conform to the original requirement.

Service. The performance of activities such as design, fabrication, inspection, repair, or installation.

Special Process. A process, the results of which are highly dependent on the control of the process or the skill of the operators, or both, and in which the specified quality cannot be readily determined by inspection or test of the product.

Shall, Should, and May. The word "shall" is used to denote a requirement, the word "should" to denote a recommendation, and the word "may" to denote permission, neither a requirement nor a recommendation.

Supplier. Any individual or organization who furnishes items or services in accordance with a procurement document. An all-inclusive term used in place of any of the following: vendor, seller, contractor, subcontractor, fabricator, consultant, and their subtier levels.

Testing. An element of verification for the determination of the capability of an item to meet specified requirements by subjecting the item to a set of physical, chemical, environmental, or operating conditions.

Traceability. The ability to trace the history, application, or location of an item and like items or activities by means of recorded identification.

Use-as-is. A disposition permitted for a nonconforming item when it can be established that the item is satisfactory for its intended use.

Verification. The act of reviewing, inspecting, testing, checking, auditing, or otherwise determining and documenting whether items, processes, services, or documents conform to specified requirements.

DEPARTMENT OF NUCLEAR ENGINEERING
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
77 Massachusetts Avenue   Cambridge, Massachusetts 02139

July 31, 1991

MIT NED Quality Assurance Manual

Table of Contents

Note: AP numbering system corresponds to Sandia National Laboratories Cask System Development Program (CSDP) Program Directives identification numbers governing the same processes.

1.0 PURPOSE AND SCOPE

1.1 The purpose and scope of this Administrative Procedure (AP) is to establish the policy, responsibility, and practice for preparation and control of APs and for revising the MIT NED QAPP. This procedure satisfies the applicable requirements of the MIT NED QAPP, Section 5.0.

2.0 POLICY

2.1 APs shall describe policy, practices to be followed, and individuals assigned responsibility for specific actions.

2.2 MIT NED shall maintain a controlled MIT NED Quality Assurance Manual containing the MIT NED QAPP and APs in accordance with the requirements of AP 3.3, Document Control.

2.3 Any MIT NED personnel may initiate a request for a new or revised AP or QAPP. Requests shall be directed to the MIT QA Coordinator who will initiate appropriate action.

2.4 MIT NED test procedures shall be prepared in accordance with AP 2.7, Test Control.

3.0 RESPONSIBILITIES AND PRACTICE

3.1 Preparing Administrative Procedures

3.1.1 MIT Principle Investigator (PI)

1. Directs that APs be prepared as necessary to implement added program requirements.

3.1.2 MIT QA Coordinator

1. Issues AP numbers according to the following categories:

A. 1.0 ADMINISTRATIVE
B. 2.0 PROGRAM CONTROL
C. 3.0 CONFIGURATION CONTROL
D. 4.0 TRAINING
E. 5.0 QUALITY
F. 6.0 SAFETY

3.1.3 Graduate Research Assistant (RA)

1. Prepare APs using the following seven major section headings:

A. 1.0 PURPOSE AND SCOPE This section contains a brief statement of the purpose of the AP. If a scope needs to be defined, it should be included in this section.

B. 2.0 <u>POLICY</u> This section contains a statement of overall policy as it pertains to the subject being addressed.

C. 3.0 <u>RESPONSIBILITIES AND PRACTICE</u> This section contains the practices to be followed, including actions to be taken, and what individual is responsible for the actions specified.

D. 4.0 <u>DEFINITIONS</u> This section defines key terms used in a special sense that will clarify the AP.

E. 5.0 <u>REFERENCES</u> This section lists the references that are associated with the AP.

F. 6.0 <u>RECORDS</u> This section lists the documents generated as a result of the procedure which are to be retained as a record.

G. 7.0 <u>APPENDICES</u> Appendices associated with an AP are identified with the AP number, page number, and an appendix number.

2. Issue APs for review and resolve comments prior to approval and issuance of the APs.

3.1.4 **MIT QA Coordinator**

1. Reviews APs to ensure that appropriate quality assurance requirements are prescribed and indicates concurrence by signing in the "Reviewed By" block.

3.1.5 MIT PI

1. Approves APs for incorporation into the controlled MIT NED AP Manual by signing in the "Approved" space of the AP form.

3.1.6 MIT QA Coordinator

1. Assigns an effective date for the approved AP to be included on the heading of the AP.

2. Coordinates issuance and distribution of all approved APs or revisions to APs.

3. Maintains controlled MIT NED AP Manuals in accordance with the requirements of AP 3.3, Document Control.

3.2 Revising Administrative Procedures and the QAPP

3.2.1 Any MIT NED personnel may initiate a request for an AP or QAPP revision.

3.2.2 The APs or the QAPP will be revised as necessary to:

A. Implement changes in contract policy and requirements

B. Reflect changes in MIT policy

C. Correct deficiencies

D. Establish policy and procedures for activities not presently covered

E. Make clarifications and other changes

3.2.3 Changes are categorized as major or minor changes. Major or minor changes shall be initiated using a Procedure Modification Request (PMR), Appendix A, and/or documentation containing information necessary to evaluate the request. The request shall be directed to the MIT QA Coordinator who will coordinate the request with responsible personnel to ensure the appropriate processing of the request, either resulting in a change to the QAPP or the procedure(s) or a response to the initiator as appropriate.

3.2.4 Minor changes do not require the same review and approval as the original procedure or QAPP. The MIT QA Coordinator is responsible to determine whether or not a proposed change is minor, to coordinate the change with other personnel as necessary and for approval of the revised procedure or QAPP. Minor changes will generally be editorial, clarification, or administrative which do not affect the purpose of the procedure or the QAPP or its effectiveness in implementing applicable requirements.

3.2.5 Major changes require the same review and approval as the original procedure or QAPP.

3.2.6 The initial issue of a procedure or the QAPP shall be designated as "Rev. A." Procedure revisions shall be indicated by sequential letters (B, C, D . . .) and changes from the previous version should be identified in the document by vertical lines adjacent to and aligned with the changed text in the right-hand margin of the pages.

3.2.7 Documents resulting from procedural or QAPP preparation and revision activities (e.g., PMRs) shall be retained as QA records.

3.3 <u>Impact Assessment</u>

3.3.1 MIT QA Coordinator

1. With the assistance of the MIT PI, as necessary, evaluates the impact of new or revised APs or QAPP on MIT NED activities previously performed to assess whether any additional actions may be required.

2. Initiates any additional action by completing a Corrective Action Report in accordance with AP 5.2, Significant Quality Problem Reporting and Corrective Action.

3. Documents this evaluation and retains as a QA record in accordance with AP 3.4, Records Management.

4.0 DEFINITIONS

4.1 <u>Administrative Procedure (AP)</u>: an AP is a formal set of written instructions that define how a specific activity is accomplished within the MIT NED.

5.0 REFERENCES

The following documents were used to compile this AP:

5.1 SNL CSDP PD 1.1, Preparation and Control of Program Directives

5.2 MIT NED QAPP

5.3 MIT NED AP 3.3, Document Control

5.4 MIT NED AP 3.4, Records Management

5.5 MIT NED AP 5.2, Significant Quality Problem Reporting and Corrective Actions

5.6 MIT NED AP 2.7, Test Control

6.0 RECORDS

6.1 MIT NED APs, MIT NED QAPP, Procedure Modification Requests, impact assessments, and Corrective Action Reports are QA records and shall be maintained in accordance with MIT NED AP 3.4, Records Management.

7.0 APPENDICES

7.1 Appendix A, Procedure Modification Request Form

APPENDIX A

PROCEDURE MODIFICATION REQUEST FORM

To: MIT QA Coordinator

From: ______________________________ Date: ___/___/___

Modification of Procedure (Number): ____________ Current Revision: ____

Title (Optional): ______________________________

Deficiency or Problem(s), and Suggested Solution(s):

(See Attached) ____

Justification for Modification (and Reference Documents): ______________

Other Procedures/Documents Affected: ______________

FORWARD TO MIT QA COORDINATOR

Request is: ____ Approved, ____ Rejected, ____ Other Dispositions.
Comments: ______________________________

Conflict With APs/QAPP or Other Procedures: ____ Yes, ____ No.
Comments: ______________________________

Procedure Modification is Classified as (Mark One): ____ Major, ____ Minor.

APPROVALS

MIT QA Coordinator: ______________________ Date: ___/___/___

Author: ______________________ Date: ___/___/___

MIT Principle Investigator: ______________________ Date: ___/___/___

MIT NED Administrative Procedure	Title: Commitment Tracking	No. 1.3 Page 1 of 3 Date: 07/31/91 Revision: B
Reviewed by: [signature]	Approved: [signature]	

1.0 PURPOSE AND SCOPE

1.1 The purpose and scope of this Administrative Procedure (AP) is to establish the policy, responsibilities, and practices for a system of tracking external action item commitments for the MIT NED.

2.0 POLICY

2.1 The MIT NED shall track and manage the completion of assigned external action item commitments and maintain a history of completion of these commitments.

3.0 RESPONSIBILITIES AND PRACTICE

3.1 MIT Principle Investigator (PI)

3.1.1 ensures that external action item commitments are managed under at tracking system.

3.1.2 approves and assigns external action item commitments to be tracked.

3.1.3 ensures that completion of action items is entered in the commitment tracking system as completion is accomplished.

3.1.4 reviews the outstanding commitments with MIT NED personnel during meetings to remind cognizant personnel of actions and to update status.

3.1.5 transfers completed items to the history file after they have been published as being complete.

3.2 Graduate Research Assistants (RAs)

3.2.1 complete assigned action item commitments and inform the MIT PI of completion. In the event the original action item commitment date cannot be met, RAs will negotiate a new date with the MIT PI.

4.0 DEFINITIONS

None.

5.0 REFERENCES

The following documents were used to compile this AP:

5.1 SNL CSDP PD 1.3, Commitment Tracking

5.2 MIT NED QAPP

5.3 MIT NED AP 3.4, Records Management

6.0 RECORDS

6.1 Commitment Tracking Assignment Sheets (Appendix A) and associated documentation are QA records and shall be maintained in accordance with AP 3.4, Records Management.

7.0 APPENDICES

7.1 Appendix A, Commitment Tracking Assignment Sheet

APPENDIX A

COMMITMENT TRACKING ASSIGNMENT SHEET

Task No: ______________ Date: __/__/__

Task Assigned to: ______________________________

Response due date: __/__/__

Task Origin: ______________________________

Task:

Supporting Documentation Attached:

Provide documentation that this task has been completed by the due date given above. In the event the commitment due date cannot be met, contact me to negotiate a new date.

____
MIT Principle Investigator

MIT NED Administrative Procedure	Title: Organization	No. 1.4 Page 1 of 6 Date: 07/31/91 Revision: C
Reviewed by: *[signature]*	Approved: *[signature]*	

1.0 PURPOSE AND SCOPE

1.1 The purpose and scope of this Administrative Procedure (AP) is to define the organization and responsibilities of the MIT NED quality activities. This procedure satisfies the applicable requirements of the MIT NED QAPP, Section 1.0.

2.0 POLICY

2.1 This procedure applies to activities performed by MIT NED personnel to support quality activities.

3.0 RESPONSIBILITIES AND PRACTICE

3.1 MIT Principle Investigator (PI) shall be responsible for the following:

3.1.1 overall implementation of the MIT NED QAPP

3.1.2 resolving disputes involving quality

3.1.3 overall administration of the activities to support the quality work

3.1.4 the preparation, review, approval, distribution, and control of APs in accordance with AP 1.1, Preparation and Control of Administrative Procedures

3.1.5 approving test procedures in accordance with AP 2.7, Test Control

3.1.6 approving Purchase Requisitions in accordance with AP 3.2, Preparation and Control of Procurement Documents

3.1.7 overall document control in accordance with AP 3.3, Document Control

3.1.8 assuring the indoctrination and training of MIT NED personnel in accordance with AP 4.1, Indoctrination and Training

3.1.9 establishing and maintaining effective communication between MIT and others to facilitate quality information reporting in accordance with AP 5.1, Quality Information Reporting

3.1.10 ensuring that significant quality problems are documented as Corrective Action Reports and distributed, corrected, verified, and approved in accordance with AP 5.2, Significant Quality Problem Reporting and Corrective Action

3.1.11 ensuring that the MIT NED is audited in accordance with AP 5.3, Quality Audit

3.1.12 ensuring the overall effectiveness and implementation of the qualification program of inspection and test personnel in accordance with AP 5.7, Qualification of Inspection and Test Personnel

3.1.13 approving the MIT NED QAPP

3.1.14 commitment tracking in accordance with AP 1.3, Commitment Tracking

3.2 <u>MIT QA Coordinator</u> shall be responsible for the following:

3.2.1 reviewing, concurring, and assessing the impact of APs and the QAPP in accordance with AP 1.1, Preparation and Control of Administrative Procedures

3.2.2 reviewing and approving test procedures in accordance with AP 2.7, Test Control

3.2.3 verifying that measuring and test equipment used by MIT NED personnel is calibrated and controlled in accordance with AP 2.8, Control of Measuring and Test Equipment

3.2.4 assisting the Graduate Research Assistant in determining QA requirements and for reviewing and approving Purchase Requisitions in accordance with AP 3.2, Preparation and Control of Procurement Documents

3.2.5 maintaining documented evidence of indoctrination and training

3.2.6 concurring with quality information provided in the Quality Information Report in accordance with AP 5.1, Quality Information Reporting

3.2.7 evaluating, concurring, tracking, and closing Corrective Action Reports (CARs) in accordance with AP 5.2, Significant Quality Problem Reporting and Corrective Action

3.2.8 implementing the Quality Audit Program in accordance with AP 5.3, Quality Audit and AP 5.5, Auditor/Lead Auditor Qualification and Certification

3.2.9 assisting the Graduate Research Assistant in determining the Quality Program levels of effort in accordance with AP 5.6, Quality Program Levels of Effort

3.2.10 evaluating, concurring, tracking, and closing Nonconformance Reports in accordance with AP 5.8, Control of Nonconforming Items

3.2.11 establishing and maintaining current the MIT NED Quality Assurance Manual

3.2.12 issuing Stop Work Requests in accordance with AP 5.4, Stop Work Request

3.2.13 administration of MIT NED QA records

3.3 Graduate Research Assistant shall be responsible for the following:

3.3.1 overall testing requirements in accordance with AP 2.7, Test Control

3.3.2 assuring, together with the MIT QA Coordinator, that measuring and test equipment is calibrated and controlled in accordance with AP 2.8, Control of Measuring and Test Equipment

3.3.3 handling, identification, storage, and shipment of items in accordance with AP 2.9, Handling, Storage, and Shipping

3.3.4 initiating and determining requirements for Purchase Requisitions in accordance with AP 3.2, Preparation and Control of Procurement Documents

3.3.5 initiating, transmitting, evaluating, concurring, and ensuring timely and effective corrective action of CARs in accordance with AP 5.2, Significant Quality Problem Reporting and Corrective Action

3.3.6 determining the appropriate Quality Program level of effort and for implementing the appropriate quality requirements and controls for each task in accordance with AP 5.6, Quality Program Levels of Effort

3.3.7 evaluating, concurring, distributing, and ensuring timely and effective corrective action of Nonconformance Reports in accordance with AP 5.8, Control of Nonconforming Items

3.3.8 ensuring that inspections required to verify conformance of an item or activity to specified requirements are planned and executed in accordance with AP 2.10, Inspection

3.4 MIT NED Personnel shall be responsible for the following:

3.4.1 adherence to the requirements of the MIT NED QAPP and the APs and to initiate revisions when identified

3.4.2 completing assigned action item commitments

3.4.3 verifying that measuring and test equipment is calibrated and controlled prior to and during usage and for reporting equipment found out of calibration in accordance with AP 2.8, Control of Measuring and Test Equipment

3.4.4 assuring that items are properly handled, identified, stored, and shipped in accordance with AP 2.9, Handling, Storage, and Shipping

3.4.5 initiating corrective action as directed in CARs in a timely and effective manner

3.4.6 initiating Nonconformance Reports and tagging or segregating the item in accordance with AP 5.8, Control of Nonconforming Items

4.0 DEFINITIONS

None.

5.0 REFERENCES

The following documents were used to compile this AP:

5.1 SNL CSDP PD 1.4, Organization

5.2 MIT NED QAPP

5.3 MIT NED AP 1.1, Preparation and Control of Administrative Procedures

5.4 MIT NED AP 1.3, Commitment Tracking

5.5 MIT NED AP 2.7, Test Control

5.6 MIT NED AP 2.8, Control of Measuring and Test Equipment

5.7 MIT NED AP 2.9, Handling, Storage, and Shipping

5.8 MIT NED AP 2.10, Inspections

5.9 MIT NED AP 3.2, Preparation and Control of Procurement Documents

5.10 MIT NED AP 3.3, Document Control

5.11 MIT NED AP 3.4, Records Management

5.12 MIT NED AP 4.1, Indoctrination and Training

5.13 MIT NED AP 5.1, Quality Information Reporting

5.14 MIT NED AP 5.2, Significant Quality Problem Reporting and Corrective Actions

5.15 MIT NED AP 5.3, Quality Audit

5.16 MIT NED AP 5.4, Stop Work Request

5.17 MIT NED AP 5.5, Auditor/Lead Auditor Qualification and Certification

5.18 MIT NED AP 5.6, Quality Program Levels of Effort

5.19 MIT NED AP 5.7, Qualification of Inspection and Test Personnel

5.20 MIT NED AP 5.8, Control of Nonconforming Items

6.0 RECORDS

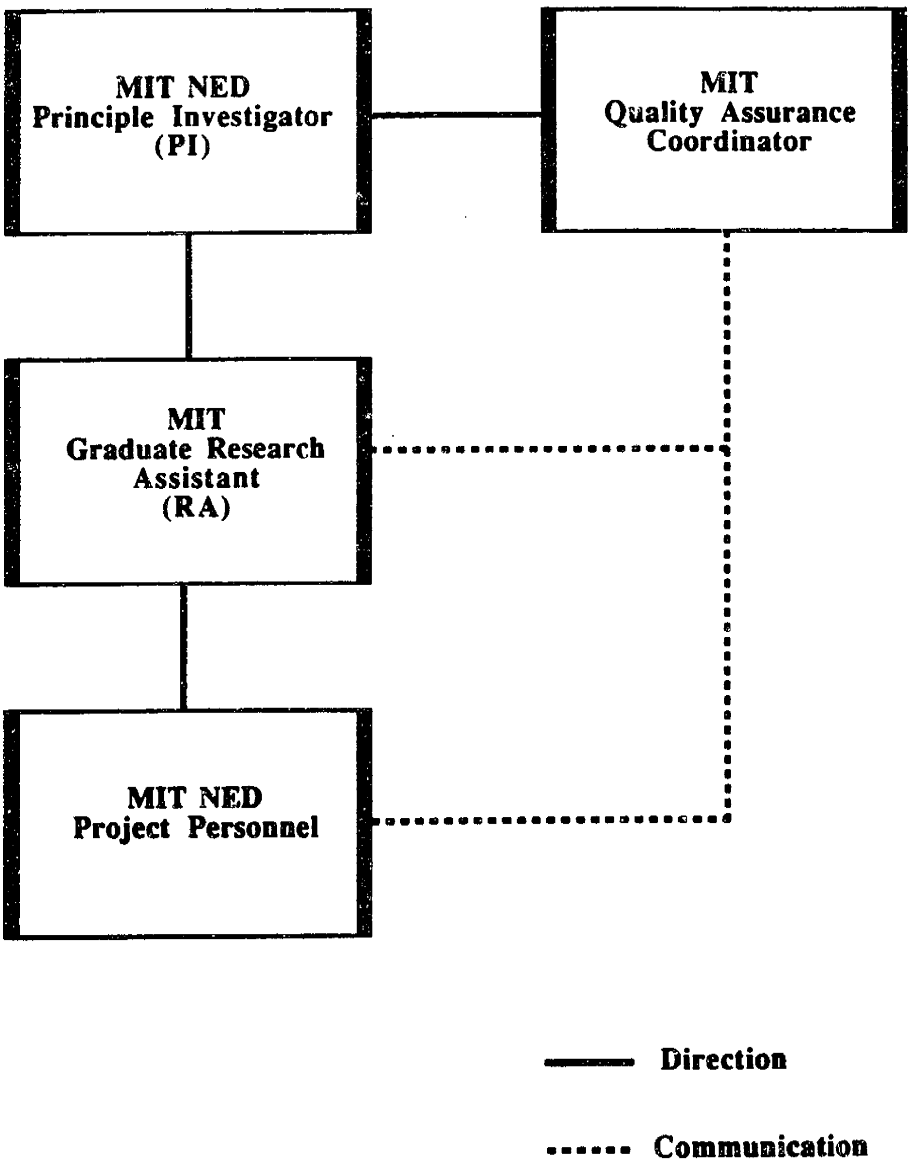
None.

7.0 APPENDICES

7.1 Appendix A, MIT NED Quality Organization Structure Chart

APPENDIX A

MIT NED QUALITY ORGANIZATION STRUCTURE CHART



MIT NED Administrative Procedure	Title: Test Control	No. 2.7 Page 1 of 6 Date: 07/31/91 Revision: C
Reviewed by: *Phyllis M. Lovett*	Approved: *Neil Todreas*	

1.0 PURPOSE AND SCOPE

1.1 The purpose and scope of this Administrative Procedure (AP) is to establish the policy, requirements, responsibility, and practice for test control. This procedure satisfies the applicable requirements of the MIT NED QAPP, Section 11.0.

2.0 POLICY

2.1 Tests conducted are generally to obtain performance data for components, subsystems, or scale models or to provide benchmark information for computer programs.

2.2 This procedure controls test procedures.

3.0 RESPONSIBILITIES AND PRACTICE

3.1 Preparing Test Procedures

3.1.1 **Graduate Research Assistant**

1. **Ensures that tests are planned and executed in accordance with documented and approved test procedures.**

2. **Ensures that test procedures are prepared in accordance with Appendix A, Preparation Instructions for Test Procedures**

3. **Ensures that test data sheets or records contain, as a minimum:**

   A. **Item tested**

   B. **Date of test**

   C. **Name of tester or data recorder**

   D. **Results and acceptability**

   E. **Action taken in connection with any deviations noted.**

4. **Ensures that the test will be conducted using qualified personnel in accordance with AP 5.7, Qualification of Inspection and Test Personnel.**

5. Ensures that hardware is handled and stored prior, during and after the test in accordance with AP 2.9, Handling, Storage and Shipping.

6. As applicable, identifies potential sources of uncertainty and error, including parameters which would be affected.

7. Ensures the precision, accuracy and control of measuring and test equipment.

8. Reviews and approves test procedures.

9. Forwards test procedure to MIT Principle Investigator for review and approval.

3.1.2 MIT Principle Investigator

1. Reviews and approves test procedures.

3.1.3 Graduate Research Assistant

1. Ensures that test procedures are controlled in accordance with AP 3.3, Document Control.

2. Ensures that tests are conducted using calibrated equipment in accordance with AP 2.8, Control of Measuring and Test Equipment.

3. Dispositions any nonconformances in accordance with AP 5.8, Control of Nonconforming Items.

4. Reviews test results to assure that test requirements have been satisfied. Resolve any discrepancies with the MIT Principle Investigator.

5. Reviews, authenticates, and transmits the test results as QA records in accordance with AP 3.4, Records Management.

3.1.4 MIT QA Coordinator

1. Issues TP numbers upon request. Each project shall be assigned a unique lead number and multiple TPs shall have secondary numbers assigned sequentially (Example: Project A - TP 1.0, 1.1, etc.; Project B - TP 2.0, 2.1, etc.).

2. Reviews TPs to ensure that appropriate quality assurance requirements are prescribed and indicates concurrence by signing in the "Approved by" block.

3. Maintains controlled TPs in accordance with AP 3.3, Document Control.

3.2 Revising Test Procedures

3.2.1 Any MIT NED Personnel may initiate revisions to Test Procedures.

3.2.2 Procedure revisions shall be documented with the Test Procedure Change Report form (Appendix B) using the change criteria in AP 1.1, Preparation and Control of Administrative Procedures.

4.0 DEFINITIONS

None.

5.0 REFERENCES

The following documents were used to compile this AP:

5.1 SNL CSDP PD 2.7, Test Control

5.2 MIT NED QAPP

5.3 MIT NED AP 3.4, Records Management

5.4 MIT NED AP 1.1, Preparation and Control of Administrative Procedures

5.5 MIT NED AP 2.10, Inspection

5.6 MIT NED AP 3.3, Document Control

5.7 MIT NED AP 5.8, Control of Nonconforming Items

5.8 MIT NED AP 2.8, Control of Measuring and Test Equipment

6.0 RECORDS

6.1 Test procedures, Test Procedure Change Reports, Master Test Procedure Change Report Index, and associate documentation are QA records and shall be maintained in accordance with AP 3.4, Records Management.

7.0 APPENDICES

7.1 Appendix A, Preparation Instructions for Test Procedures

7.2 Appendix B, MIT NED Test Procedure Change Report form

APPENDIX A

PREPARATION INSTRUCTIONS FOR TEST PROCEDURES

1. Obtain a Test Procedure (TP) number from the MIT QA Coordinator according to the following categories:

   1.0 - 99.0 Test Procedures

2. Prepare Test Procedures using the following five major section headings:

I.	Purpose	This section contains a brief statement of the purpose of the TP.
II.	Cautions	This section contains a list of the precautionary measures that should be taken with the equipment to prevent damage to the equipment or personnel safety.
III.	Required Equipment	This section lists the equipment required for the test.
IV.	Tests	This section provides instruction for setting up the test as well as steps to perform the test. Any Cautions or Notes should be placed prior to the step it applies to. Data sheets shall be provided in attachments.
V.	Acceptance Criteria	This section provides the criteria for which the test becomes acceptable

3. Obtain approval of the TP from the MIT Principle Investigator and the MIT QA Coordinator.

APPENDIX B

MIT NED TEST PROCEDURE CHANGE REPORT

Change No. ____________________ Page ____ of ____

Procedure Title: ____

Procedure No.: ____________________

Procedure Page: ____________________

Procedure Revision No.: ____________ Date: ___/___/___

Change:

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____
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Reason for Change:

____
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Comments:

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____
____
____

Approved by:

____ Date: ___/___/___
Graduate Research Assistant

____ Date: ___/___/___
MIT Principle Investigator

____ Date: ___/___/___
MIT QA Coordinator

MIT NED Administrative Procedure	Title: Control of Measuring and Test Equipment	No. 2.8 Page 1 of 3 Date: 05/28/91 Revision: B
Reviewed by: *[signature]*	Approved: *[signature]*	

1.0 PURPOSE AND SCOPE

1.1 The purpose and scope of this Administrative Procedure (AP) is to define requirements and responsibilities for the control, calibration, and maintenance of tools, gauges, instruments, and other measuring and testing devices. This procedure satisfies the applicable requirements of the MIT NED QAPP, Section 12.0.

2.0 POLICY

2.1 The requirements of this AP apply to tests performed by MIT NED.

2.2 Contractor calibration programs must meet the requirements of this AP.

3.0 RESPONSIBILITIES AND PRACTICE

3.1 The Graduate Research Assistant (RA) shall ensure that newly procured or previously used instruments, and measuring and testing equipment are calibrated with NIST standards before their use in support of data gathering activities.

3.2 Labeling of Instruments and Measuring and Test Equipment

3.2.1 Instruments and measuring and test equipment used by MIT NED shall be identified and labeled (where practical) with a readily visible label indicating calibration status. Labels reflecting an item's calibration status will be applied by calibration organizations.

3.2.2 Instruments and measuring and test equipment shall be labeled to indicate the serial number or other unique identifier, by whom it was calibrated, and when the next calibration is due. Labels, codes, or recall records for devices which are not required to be used to their full capabilities or devices which require functional check or indication only shall specify the applicable condition.

3.3 Calibration Requirements

Measuring and test equipment shall be calibrated utilizing reference standards whose calibration is certified as being traceable to the National Institute of Standards and Technology (NIST). If NIST standards do not exist, the basis for traceable calibration shall be documented by the calibrating agency. This documentation shall be approved by the Graduate Research Assistant.

3.3.1 Calibration certification shall contain, as a minimum, the following:

A. The name and serial number or other unique identifier of the device calibrated

B. The date of the calibration

C. Date indicating when the next calibration check is due

D. The printed name and signature of the person who performed the calibration.

3.3.2 Calibration intervals may be expressed in calendar time or may relate to usage.

3.3.3 Commercial, nonprecision devices, such as rulers, tape measures, levels, and liquid-filled thermometers, need not be calibrated if the equipment provides adequate accuracy. Adequate accuracy will be assumed unless otherwise stated by the Graduate Research Assistant.

3.3.4 Exceptions to the calibration of test and measuring equipment must be documented and approved by the MIT Principle Investigator and MIT QA Coordinator.

3.4 Devices That Fail Calibration

If an instrument is reported as being out of calibration, the project test personnel (in consultation with the Graduate Research Assistant) review the as-found calibration data to determine the effect of the out-of-calibration instrument on the test data. If the data are acceptable, the project test personnel and Graduate Research Assistant sign or initial the calibration sheet to indicate acceptance, and submit the calibration sheet to the MIT QA Coordinator for retention. If the Graduate Research Assistant determines that the data are questionable or unacceptable, a nonconformance report is initiated in accordance with AP 5.8, Control of Nonconforming Items.

3.5 Storage of Instruments, and Measuring and Test Equipment

The environment in which test and measuring equipment is stored, maintained, and used must be maintained to the extent necessary to assure continued measurements of required accuracy. Environmental factors that should be considered include, but are not limited to, temperature, humidity, handling and shipping, shock and vibration, radio frequency interference, electromagnetic interference, voltage stability, toxic fumes, dust, and general housekeeping duties.

3.6 The users of measuring and test equipment shall do the following:

A. Before use, determine that the device is operable, free of damage, and not overdue for calibration

B. Use and store instruments in a manner that will preserve their in-calibration status and measuring capability

C. Request a calibration check when the accuracy of measuring or test equipment is suspect.

3.7 It is the responsibility of the Graduate Research Assistant to ensure that measuring and test equipment is calibrated. This responsibility includes requesting calibration, repair, and maintenance of instruments for which the Graduate Research Assistant is accountable including the handling and packaging of those requiring shipment.

3.8 The MIT QA Coordinator shall verify that requirements of this AP are observed to ensure an effective calibration program. The MIT QA Coordinator shall ensure that records are generated and maintained which reflect the current status of compliance to requirements noted in this AP.

4.0 DEFINITIONS

4.1 Measuring and Test Equipment: devices or systems used to measure, gauge, test, or inspect in order to control or to acquire data to verify conformance to a specified requirement or to establish characteristics or values not previously known.

5.0 REFERENCES

The following documents were used to compile this AP:

5.1 SNL CSDP PD 2.8, Control of Measuring and Test Equipment

5.2 MIT NED QAPP

5.3 MIT NED AP 3.4, Records Management

5.4 MIT NED AP 5.8, Control of Nonconforming Items

6.0 RECORDS

6.1 Calibration certification records and any nonconformance reports generated are QA records and shall be maintained in accordance with AP 3.4, Records Management.

7.0 APPENDICES

None.

MIT NED Administrative Procedure	Title: Handling, Storage and Shipping	No. 2.9 Page 1 of 4 Date: 07/31/91 Revision: C
Reviewed by: Phyllis M. Lovett	Approved: Neil Todreas	

1.0 PURPOSE AND SCOPE

1.1 The purpose and scope of this Administrative Procedure (AP) is to define the requirements and methods to be used for identification, packaging, handling, shipping, preservation and storage of items to preclude damage, loss, deterioration by environmental conditions, or substitution of items. This procedure satisfies the applicable requirements of the MIT NED QAPP, Section 13.0.

2.0 POLICY

2.1 This procedure applies to items determined to be important to safety and/or retrievability in the MIT NED when these items are the responsibility of the MIT NED staff and contractors.

3.0 RESPONSIBILITIES AND PRACTICE

3.1 Compliance with this procedure will provide for the identification, packaging, handling, shipping, preservation, and storage of items and material important to safety and retrievability.

3.2 Identification This section applies to those items that require unique identification.

3.2.1 The Graduate Research Assistant (RA) will obtain MIT property identification number, if required, and ensure that the identifier is applied to the item.

3.2.2 The Graduate RA shall assign a unique identifying number/label using the scheme in Appendix A.

3.2.3 Physical identification will be used to the extent possible, either by indelible marks on the items or by physical attachment of the identification to the items and material. In cases in which physical identification is either impractical or insufficient, or would compromise the items for intended use(s), then physical separation, procedural control, or other appropriate identification will be employed.

3.2.4 Identification markings, when used, shall be applied using materials and methods which provide a clear and legible identification and do not detrimentally affect the function or service life of the item.

3.2.5 The identification will be maintained throughout the usage period of items up to and including disposal. Personnel using, moving, or handling identified items are responsible for maintaining that identification. The identification will be traceable to documents including but not limited to logs, test records, inspection documents, and nonconformance reports.

3.3 Handling, Packaging, and Shipping

3.3.1 Packaging When necessary, items shall be packed for shipping in an appropriate manner to prevent damage to the item. Aspects that may be considered in determining if specific packaging instructions are appropriate include:

A. Orientation; i.e., must the item be maintained upright, horizontal, etc. during shipment

B. Protection from moisture/wetness

C. Protection from temperature extremes, such as freezing

D. Protection from shock and/or vibration

3.3.2 Handling When determined to be necessary to ensure safe and adequate handling, special handling tools and equipment will be utilized by operators experienced or trained in their use.

3.3.3 Shipping The Graduate Research Assistant will ensure that items and material will be shipped in a manner that will protect the characteristics or function of the items and material, as well as, the identification.

3.4 Storage When not in use, items shall be placed in appropriate storage locations.

3.4.1 Individuals responsible for items covered by this procedure will ensure that such items placed in storage will be adequately protected to ensure their preservation and functioning.

4.0 DEFINITIONS

4.1 Item: an all-inclusive term that is used in place of any appurtenance, assembly, component, equipment, material, module, part, structure, subassembly, subsystem, system, unit, or prototype hardware. Documents are specifically excluded.

5.0 REFERENCES

The following documents were used to compile this AP:

5.1 SNL CSDP PD 2.9, Handling, Storage and Shipping

5.2 MIT NED QAPP

6.0 RECORDS

None.

7.0 APPENDICES

7.1 Appendix A, MIT NED Unique Identification Labeling Scheme

APPENDIX A

MIT NED UNIQUE IDENTIFICATION LABELING SCHEME

Each individual item shall be identified with its own label containing a unique identification number. The number shall be broken down into three (3) identification methods:

1. the item's system,
2. the item's function, and
3. a sequential number of similar items in the system.

Sample Systems	System Identification Abbreviation
Heater Rod System	ROD
Boundary Condition Box System	BCB
Containment Vessel System	CV
Data Acquisition System	DAU

Sample Functions	Function Identification Abbreviation
Valve	VAL
Heater	HTR
Controller	C
Alarm	ALA
Voltmeter	V
Ammeter	A
Wattmeter	W
Pressure	P
Relief Valve	RV
Vacuum Pump	VP
Thermometer	TH
Variac	VARIAC
Computer	COM
Multiplexer Card	M
Gauge	G
Printer	PRT

Example: ROD-A-1 and ROD-A-2
There are 2 ammeters in a heater rod power system. Each identification number shall be associated with a unique item.

MIT NED Administrative Procedure	Title: Inspection	No. 2.10 Page 1 of 4 Date: 05/28/91 Revision: B
Reviewed by: Phyllis M. Lovett	Approved: Neil Todreas	

1.0 PURPOSE AND SCOPE

1.1 The purpose and scope of this Administrative Procedure (AP) is to establish the requirements for planning, execution, documentation, review, and approval of inspections performed on MIT NED activities. This procedure satisfies the applicable requirements of the MIT NED QAPP, Section 10.0.

2.0 POLICY

2.1 Inspection shall be performed, as applicable, on MIT NED activities.

2.2 Receipt inspections are performed in accordance with AP 3.2, Preparation and Control of Procurement Documents.

3.0 RESPONSIBILITIES AND PRACTICE

3.1 MIT QA Coordinator

1. Assists the Graduate Research Assistant in the identification, execution, and review of inspections.

3.2 Graduate Research Assistant

1. Ensures that inspections are required to verify conformance of an item to specified requirements and to verify that the item continues to remain within specified limits.

2. Inspection planning shall provide:

   (a) criteria for determining when inspections are to be conducted

   (b) identification of required procedures, drawings, and specifications including revisions

   (c) specification of necessary measuring and test equipment.

3. Ensures that inspections for acceptance are performed and documented by persons other than those who performed the work being inspected.

4. Ensures that inspection personnel are qualified to perform the verification activity.

5. Ensures that receipt inspections of procured items are performed as required in procurement document.

6. Ensures that the inspection cover completeness, markings, calibration, protection from damage, and other characteristics as required to verify quality and performance.

7. Ensures that inspections are documented on an MIT NED Inspection Report, Appendix A.

8. Review and approves inspection results.

9. Ensures that identified nonconformances are reported and resolved in accordance with AP 5.8, Control of Nonconforming Items.

3.3 MIT QA Coordinator

1. Approves Inspection Reports.

2. Ensures that inspection results are documented and retained as QA records in accordance with AP 3.4, Records Management.

4.0 DEFINITIONS

None.

5.0 REFERENCES

The following documents were used to compile this AP:

5.1 SNL CSDP PD 2.10, Inspection

5.2 MIT NED QAPP

5.3 MIT NED AP 3.4, Records Management

5.4 MIT NED AP 5.8, Control of Nonconforming Items

5.5 MIT NED AP 3.2, Preparation and Control of Procurement Documents

6.0 RECORDS

6.1 Inspection records are QA records and shall be maintained in accordance with AP 3.4, Records Management.

7.0 APPENDICES

7.1 Appendix A, MIT NED Inspection Report form

APPENDIX A

MIT NED INSPECTION REPORT

Report No. ______________________ Date: ___/___/___ Page ____ of ____

To: ____

From: ______________________________________

Item(s) and Characteristic(s) Inspected:

Objective Evidence of the Results and Acceptability:

Inspection Criteria or Reference Document(s) Used to Determine Acceptance:

Measuring and Test Equipment Used During Inspection:

MIT NED Nonconformance Report Issued: [ ] Yes [ ] No

NCR No: ______________________

Inspected by: ____________________________________ Date: ___/___/___

Approved by: ____________________________________ Date: ___/___/___
MIT QA Coordinator

MIT NED Administrative Procedure	Title: Preparation and Control of Procurement Documents	No. 3.2 Page 1 of 4 Date: 05/28/91 Revision: B
Reviewed by: Phyllis N. Lovett	Approved: Mark Andrews	

1.0 PURPOSE AND SCOPE

1.1 The purpose and scope of this Administrative Procedure (AP) is to describe the preparation, quality assurance, and distribution of procurement documentation for the purchase of material, equipment, and services. This AP provides instruction for assuring the quality of material, equipment, and services purchased by MIT NED and satisfies the applicable requirements of the MIT NED QAPP, Section 4.0 and 7.0.

2.0 POLICY

2.1 Measures shall be established to assure that purchased material, equipment, and services conform to the procurement documents. Applicable requirements shall be included or referenced in the contracts for procurement of material, equipment, and services. To the extent necessary, contracts shall require contractors to have a suitable QA program.

3.0 RESPONSIBILITIES AND PRACTICE

3.1 Initiating a Purchase Requisition (PR)

3.1.1 The Graduate Research Assistant (RA) is responsible for filling out an MIT Purchase Requisition/Change Requisition (PR/CR) form, including the following, as applicable:

A. Suggested source

B. A description of the material, equipment, and/or services to be procured

C. The design basis; e.g., drawings, specifications, instructions, and standards. Such documents are specified by their control features (date, issue, revision, amendment) to assure that the subsequent contract is established on the latest applicable design basis, and to facilitate control of future changes

D. The QA requirements appropriate for the nature of the procured item

E. Quantities, desired delivery dates, and delivery instructions

G. Cost estimate and other financial and administrative information (e.g., account number, etc.)

3.1.2 The QA Coordinator initials the PR/CR next to the APPROVED BY block to indicate approval of quality requirements and forwards the PR/CR to the MIT Principle Investigator.

3.1.3 The MIT Principle Investigator (or his designee) approves the PR/CR by signing the APPROVED BY block and returns it to the requestor.

3.1.4 The requestor obtains a Purchase Order Number from the Purchasing Organization. The Purchasing Organization processes the purchase.

3.1.5 The requestor forwards the original PR/CR (only) to the MIT NED Administrative Office for financial processing and a copy of the PR/CR and any associated documentation to the MIT QA Coordinator.

3.1.6 The MIT QA Coordinator retains the PR/CR and associated documentation as a QA record.

3.2 <u>Inspection and Acceptance</u>

3.2.1 The Graduate Research Assistant, in conjunction with the MIT QA Coordinator, arranges for inspection and acceptance of the procured items.

3.2.2 Receiving inspections shall be coordinated with the review of supplier documentation when procurement documents require supplier documentation be furnished.

3.2.3 If the items or materials do not meet procurement document requirements, an NCR will be initiated and resolved in accordance with AP 5.8, Control of Nonconforming Items.

3.2.4 For commercial grade items, the following shall be determined by the requestor:

A. No shipment damage

B. Received item is the item ordered

C. If appropriate, inspection and testing to determine if the item conforms to manufacturer's published specifications

D. Requested documentation has been received and is acceptable.

3.2.5 The requester shall ensure that documentation of all activities regarding the acceptance of the items or materials is forwarded to the MIT QA Coordinator. This documentation shall be retained as a QA record. Minimum documentation consists of accepted Invoice forms.

3.3 <u>Purchase Closure</u>

3.3.1 The requestor shall sign and date the Invoice form to indicate that all work specified in the PR/CR has been completed and accepted.

3.3.2 The requestor shall send the original Invoice form (only) to the MIT NED Administrative Office for financial closure and a copy of the Invoice form and associated documentation to the MIT QA Coordinator for retention as a QA record.

3.4 Change Requisitions

3.4.1 A CR may be initiated by the requestor to alter the Purchase Order. A CR is written with the appropriate changes and is submitted for formal review and sign-off.

3.5 Commercial Items

3.5.1 Off-the-shelf items shall be ordered according to manufacturer's product serial number or description. Reference to a recognized standard or specification shall be made when a standard product is manufactured by numerous companies; i.e., sheet metal.

3.5.2 Some commercial items are available through the MIT Laboratory Supply Office. Although a PR does not require the approval of the MIT Principle Investigator, the requester is responsible for the complete quality inspection (correct item, correct quantity, freedom from damage, correction operation, etc.). In all cases, the requester is responsible for the final acceptance or rejection of purchased items.

4.0 DEFINITIONS

4.1 Change Requisition (CR): the document submitted to the administrative office/purchasing organization which defines and authorizes a change to a purchase order.

4.2 Purchase Order (PO): the document prepared by the purchasing organization to implement the requirements of the Purchase Requisition.

4.3 Purchase Requisition (PR): the document originated by the MIT NED requester and sent to the purchasing organization which defines and authorizes a procurement action.

5.0 REFERENCES

The following documents were used to compile this AP:

5.1 SNL CSDP PD 3.2, Preparation and Control of Procurement Documents

5.2 MIT NED QAPP

5.3 MIT NED AP 3.4, Records Management

5.4 MIT NED AP 5.6, Quality Program Levels of Effort

5.5 MIT NED AP 5.8, Control of Nonconforming Items

6.0 RECORDS

6.1 The following procurement documents generated by this procedure are QA records and shall be maintained in accordance with AP 3.4, Records Management:

1. Purchase Requisitions and associated documentation
2. Receipt Inspection records
3. Change Requisitions and associated documentation
4. Significant correspondence related to the procurement
5. Invoice forms and associate documentation.

7.0 APPENDICES

None.

MIT NED Administrative Procedure	Title: Document Control	No. 3.3 Page 1 of 4 Date: 07/31/91 Revision: C
Reviewed by: Phyllis M. Lovett	Approved: Neil Todreas	

1.0 PURPOSE AND SCOPE

1.1 The purpose and scope of this Administrative Procedure (AP) is to establish policy, requirements, and practices for the preparation, release, and revision of controlled documents within the MIT NED. This procedure satisfies the applicable requirements of the MIT NED QAPP, Section 6.0.

2.0 POLICY

2.1 Selected MIT NED documents are controlled in order to assure that activities are performed to the most current information incorporated into documents which are procedurally reviewed, approved and distributed to ensure the highest quality of work.

2.2 MIT NED controlled documents are the MIT NED QAPP, APs, Test Procedures (TPs), and Engineering Drawings.

3.0 RESPONSIBILITIES AND PRACTICE

3.1 MIT Principle Investigator (PI)

1. Ensures that the requirements of this AP are adhered to within MIT NED.
2. Ensures that changes in program requirements are incorporated into affected program documents.

3.2 Graduate Research Assistants (RAs)

1. Prepare the required document or changes according to the format required for the particular document as outlined in APs.
2. Ensure that Engineering Drawings and Specifications required to support the testing activities are prepared.
3. Document changes to original issue Engineering Drawings and Specifications.
4. Record changes to test procedures on a Test Procedure Change Report in accordance with AP 2.7, Test Control.
5. Ensure that controlled documents delineate those documents generated as a result of implementation and which are to become QA records.
6. Obtain required reviews and approval in accordance with APs.

3.3 MIT QA Coordinator

1. Reviews and approves controlled documents in accordance with approved procedures.

2. Maintains a log of the MIT NED Procedure Modification Request forms.

3. Coordinates the printing of and distribution of released MIT NED documents according to controlled distribution lists.

4. As a minimum, the MIT Principle Investigator, the MIT QA Coordinator, and Graduate Research Assistants shall receive a controlled copy of the MIT QAPP and APs.

5. Maintains a controlled distribution list for each controlled document.

6. Distributes controlled documents using a transmittal form (Appendix A) and retains the returned, signed transmittal forms.

7. Maintains a Controlled Documents List (CDL) showing the current revision and release status of the MIT NED controlled documents.

8. Maintains an original history file of MIT NED controlled documents including the appropriate document revision forms.

4.0 DEFINITIONS

4.1 Document Control: the activity of assuring that documents are reviewed for adequacy, approved for release by authorized personnel, and distributed to and used at the location where the prescribed activity is performed.

5.0 REFERENCES

The following documents were used to compile this AP:

5.1 SNL CSDP PD 3.3, Document Control

5.2 MIT NED QAPP

5.3 MIT NED AP 3.4, Records Management

5.4 MIT NED AP 2.7, Test Control

6.0 RECORDS

6.1 Procedure Modification Request, Test Procedure Change Report, and the history file of controlled documents including documented reviews are QA records and shall be maintained in accordance with AP 3.4, Records Management.

7.0 APPENDICES

7.1 Appendix A, Controlled Document Transmittal/Acknowledgment form

APPENDIX A

MIT NED CONTROLLED DOCUMENT TRANSMITTAL/ACKNOWLEDGMENT FORM

Document Title: ____

Document ID: ________________________

Control No. ____________ is issued to:

______________________________________ (Name) ______________ (Title)

on ________________ (Date)

Controlled Copy ( ) Revisions will be provided

Uncontrolled Copy ( ) For information only, revisions will not be provided

Summary: Issuance of ____

____

____

____ (List Documents)

Special Directions:

Please check appropriate box(es), sign and date.

[ ] I have performed the above action(s) and, if applicable superseded portions have been discarded or marked "Superseded" and placed in a separate location.

[ ] I have verified that the document received is the document described on the transmittal form, in terms of content and number and order of pages, and have notified the sender of any discrepancies.

[ ] I do not require this document; please remove me from distribution. Document has been destroyed.

Signature: ______________________________________ Date: ___/___/___

****

Please return this form by ___/___/___ to:

MIT Quality Assurance Coordinator
Nuclear Engineering Department

MIT NED Administrative Procedure	Title: Records Management	No. 3.4 Page 1 of 3 Date: 05/28/91 Revision: B
Reviewed by: Phyllis M. Lovett	Approved: [signature]	

1.0 PURPOSE AND SCOPE

1.1 The purpose and scope of this Administrative Procedure (AP) is to establish the applicability, requirements, responsibilities, and procedure for the managing of records within the MIT NED. This procedure satisfies the applicable requirements of the MIT NED QAPP, Section 17.0.

2.0 POLICY

2.1 Typical documents to be retained as a record are listed in Appendix A.

3.0 RESPONSIBILITIES AND PRACTICE

3.1 MIT Principle Investigator (PI)

3.1.1 Shall have overall responsibility for the generation and retention of QA records.

3.1.2 Shall ensure that the records system is effective.

3.2 MIT NED Personnel

3.2.1 Shall ensure that documents procedurally designated as QA records are generated, reviewed, and approved in accordance with procedure and are complete, legible, traceable, and accurate.

3.2.2 Shall forward the record to the Graduate Research Assistant or directly to the MIT QA Coordinator, as appropriate.

3.3 Graduate Research Assistant or MIT QA Coordinator

3.3.1 Shall ensure that documents which are to become records are noted in procedures.

3.3.2 Shall inventory the records and discard duplicates.

3.3.3 Shall assign a file code to the records.

3.3.4 Shall ensure that a copy of QA records are forwarded to and retained by the MIT QA Coordinator.

3.3.5 May retain a working copy of the record as appropriate.

3.4 MIT QA Coordinator

3.4.1 Shall receive, inventory, file, retain, and maintain MIT NED records.

3.4.2 Shall assure that applicable specifications, documents, procedures, or instructions specify the records to be generated, supplied, or maintained.

3.4.3 Shall retain a redundant copy of QA records.

4.0 DEFINITIONS

4.1 Quality Assurance (QA) Record: an individual document or other item that has been executed, completed, and approved and that furnishes evidence of the quality and completeness of data (including raw data), items, and activities affecting quality; documents prepared and maintained to demonstrate implementation of quality assurance programs (e.g., audit and inspection reports); procurement documents; other documents such as plans, correspondence, documentation of telephone conversations, specification, technical data books, papers, photographs, and data sheets; items such as magnetic media, physical samples; and other materials that provide data and document quality regardless of physical form or characteristic. A completed record is a document or item (and documentation) which will receive no more entries, whose revisions would normally consist of a reissue of the document (or documentation), and that is signed and dated by the originator and, as applicable, by approval personnel.

4.2 Record Package: a collection of records supporting one topic (subject) that is filed as a case file; e.g., QA audit file, contract or procurement file, or an engineering drawing package. The file will be held by the originating individual until the transaction is completed. It will then be indexed and processed as one record.

5.0 REFERENCES

The following documents were used to compile this AP:

5.1 SNL CSDP PD 3.4, Records Management

5.2 MIT NED QAPP

6.0 RECORDS

None.

7.0 APPENDICES

7.1 Appendix A, Typical Records To Be Maintained by MIT NED

APPENDIX A

TYPICAL QA RECORDS TO BE MAINTAINED BY MIT NED

Administrative Procedures
Audit Plans
Audit Reports
Audit Schedules
Auditor Qualification Form
Calibration Records
Commitment Tracking Assignment Sheets
Confirmation of Training Records
Corrective Action Reports
Document Revision Requests
Engineering Drawings
Indoctrination and Training Records
Inspection and Test Personnel Certification Records
Inspection Reports
Lead Auditor Qualification Form
Logbooks (or copies thereof)
Monthly Status Reports
Nonconformance Reports
Personnel Qualification Data Sheets
Procedure Modification Request Forms
Procurement Documentation
Purchase Orders
Purchase Requisitions
Quality Assurance Audit Personnel Qualifications Update
Quality Assurance Program Plan
Quality Information Report
Quality Level Assignment Checklists
Revised Document Reading Records
Stop Work Requests
Test Procedures

MIT NED Administrative Procedure	Title: Indoctrination and Training	No. 4.1 Page 1 of 7 Date: 07/31/91 Revision: B
Reviewed by: Phyllis L. Lovett	Approved: Neil Todreas	

1.0 PURPOSE AND SCOPE

1.1 The purpose and scope of this Administrative Procedure (AP) is to establish the policy, responsibilities, and requirements for the indoctrination and training of MIT NED personnel. This procedure satisfies the applicable requirements of the MIT NED QAPP, Section 2.0.

2.0 POLICY

2.1 MIT NED personnel performing activities affecting quality, shall receive training and indoctrination requisite for their activities and level of responsibility. Documented evidence of indoctrination and training activities shall be maintained by the MIT QA Coordinator.

3.0 RESPONSIBILITIES AND PRACTICE

3.1 Graduate Research Assistant

3.1.1 Ensures by review of the individual's qualifications that the individual are qualified to perform their assigned duties.

3.1.2 Ensures indoctrination and training of the personnel performing activities affecting quality.

3.1.3 Initiates periodic training sessions for personnel and requires review of revised program documents, as necessary.

3.1.4 Ensures that indoctrination and training activities are documented and maintained either in a training file or in the respective personnel files.

3.1.5 Requires as part of the indoctrination and training program, that program personnel review and have a working knowledge of the following documents:

A. MIT NED QA Program Plan

B. MIT NED Administrative Procedures

3.1.6 Monitors the performance of personnel doing work affecting quality to determine the need for retraining.

3.2 MIT NED Personnel

3.2.1 Fulfill indoctrination and training requirements

3.3 MIT QA Coordinator

3.3.1 Maintains documented evidence of Personnel Qualification Data Sheets and indoctrination and training activities.

3.3.2 Reviews annually personnel qualification and indoctrination and training records.

3.4 Qualification of Personnel

3.4.1 Documentation of personnel qualifications will be recorded on Personnel Qualification Data Sheets (Appendix A). These data sheets will include, as a minimum, the participant's name, education, experience, and other qualifications. The data sheets are approved by the Graduate Research Assistant and the MIT Principle Investigator.

3.4.2 The MIT QA Coordinator will file the Personnel Qualification Data Sheets as part of the quality assurance records.

3.4.3 The MIT QA Coordinator in conjunction with the MIT Principle Investigator will review the data sheets annually.

3.5 Indoctrination and Training Program

3.5.1 Initial training assignments shall be documented on the MIT NED Indoctrination and Training Record, Appendix B. Subsequent training assignments to revised APs or QAPP shall be documented on the MIT NED Revised Document Reading Record, Appendix D.

3.5.2 Indoctrination and training records will be reviewed annually by the MIT QA Coordinator for completeness.

3.6 Confirmation of Training

3.6.1 Appendix C, MIT NED Confirmation of Training Record, shall be used to ratify the satisfactory completion of training. All training completed shall be noted on the Confirmation Record and approved by the MIT Principle Investigator and the MIT QA Coordinator.

4.0 DEFINITIONS

None.

5.0 REFERENCES

The following documents were used to compile this AP:

5.1 SNL CSDP PD 4.1, Indoctrination and Training

5.2 MIT NED QAPP

5.3 MIT NED AP 3.4, Records Management

6.0 RECORDS

6.1 Indoctrination and Training Records, Confirmation of Training Records, Revised Document Reading Records, and Personnel Qualification Data Sheets shall be maintained in accordance with AP 3.4, Records Management.

7.0 APPENDICES

7.1 Appendix A, MIT NED Personnel Qualification Data Sheet

7.2 Appendix B, MIT NED Indoctrination and Training Record

7.3 Appendix C, MIT NED Confirmation of Training Record

7.4 Appendix D, MIT NED Revised Document Reading Record

APPENDIX A

MIT NED PERSONNEL QUALIFICATION DATA SHEET

NAME: ______________________________ POSITION: ____________________

Signature: __________________________ Date: ___/___/___

Total Experience Years: __________

Education:

____
____
____
____
____
____

Experience:

____
____
____
____
____
____

Other:

____
____
____
____
____
____

Management Approval:

______________________ ___/___/___ ______________________ ___/___/___
Graduate Research Assistant Date MIT Principle Investigator Date

APPENDIX B

MIT NED INDOCTRINATION AND TRAINING RECORD

NAME: ______________________ POSITION: ______________

A.	ADMINISTRATIVE PROCEDURES		REVISION	INITIAL & DATE
	1.1	Preparation and Control of Administrative Procedures	______	______
	1.3	Commitment Tracking	______	______
	1.4	Organization	______	______
	2.7	Test Control	______	______
	2.8	Control of Measuring and Test Equipment	______	______
	2.9	Handling, Storage and Shipping	______	______
	2.10	Inspection	______	______
	3.2	Preparation and Control of Procurement Documents	______	______
	3.3	Document Control	______	______
	3.4	Records Management	______	______
	4.1	Indoctrination and Training	______	______
	5.1	Quality Information Reporting	______	______
	5.2	Significant Quality Problem Reporting and Corrective Action	______	______
	5.3	Quality Audit	______	______
	5.4	Stop Work Request	______	______
	5.5	Auditor/Lead Auditor Qualification and Certification	______	______
	5.6	Quality Program Levels of Effort	______	______
	5.7	Qualification of Inspection and Test Personnel	______	______
	5.8	Control of Nonconforming Items	______	______
B.	OTHER DOCUMENTS		REVISION	INITIAL & DATE
	MIT NED QA Program Plan		______	______
	______________________		______	______

I verify that I have reviewed and have a working knowledge of the above mentioned documents and that I have completed all additional training requirements noted herein.

Signature: ______________________ Date: ___/___/___

This form must be completed and forwarded to the MIT QA Coordinator by ___/___/___.

Reviewed by:

______________________ ______________________

MIT Principle Investigator MIT QA Coordinator

APPENDIX C

MIT NED CONFIRMATION OF TRAINING RECORD

NAME: ______________________________ POSITION: __________________

has completed the following training as part of the MIT NED Indoctrination and Training Program by:

[ ] Completion of the MIT NED Indoctrination and Training Record

[ ] Completion of other assigned training noted below:

____
____
____
____
____
____

Approved:

______________________________ ______________________________
MIT Principle Investigator MIT QA Coordinator

APPENDIX D

MIT NED REVISED DOCUMENT READING RECORD

NAME: ______________________________ POSITION: ____________________

INSTRUCTIONS

1. The document(s) listed below represent a training requirement that must be fulfilled before training will be confirmed complete. Please initial and date to signify you have completed this activity.
2. USE BLACK INK TO COMPLETE THIS FORM.
3. IN ALL CASES, read the procedure and familiarize yourself with its contents.

Document/Revision	Assigned Target Date	I have read the procedure and am familiar with its contents.

My signature indicates that I have performed the indoctrination or training activities shown for the assigned procedure(s).

Signature: ______________________________ Date: ___/___/___

****

Please return this form be ___/___/___ to:

MIT QA Coordinator
Nuclear Engineering Department

MIT NED Administrative Procedure	Title: Quality Information Reporting	No. 5.1 Page 1 of 2 Date: 03/25/91 Revision: A
Reviewed by: [signature]	Approved: [signature]	

1.0 PURPOSE AND SCOPE

1.1 The purpose and scope of this Administrative Procedure (AP) is to describe the method for obtaining data and reporting information and status of the QA Program. This procedure satisfies the applicable requirements of the MIT NED QAPP, Section 2.0.

2.0 POLICY

2.1 This procedure applies to MIT NED QA activities.

3.0 RESPONSIBILITIES AND PRACTICE

3.1 MIT QA Coordinator

3.1.1 Shall prepare and submit at least quarterly a Quality Information Report for distribution to the following:

A. MIT Principle Investigator

B. Others as determined by the MIT QA Coordinator.

3.1.2 Shall include in the quality information, when applicable, an assessment of the following:

A. QA Program status including development status

B. Performance of quality activities such as audits, inspection, and tests.

3.1.3 Shall initiate any corrective action or QA Program revisions required as a result of the quality information.

4.0 DEFINITIONS

None.

5.0 REFERENCES

The following documents were used to compile this AP:

5.1 SNL CSDP PD 5.1, Quality Information Reporting

5.2 MIT NED QAPP

5.3 MIT NED AP 3.4, Records Management

6.0 RECORDS

6.1 The Quality Information Report is a QA record and shall be maintained in accordance with AP 3.4, Records Management.

7.0 APPENDICES

None.

MIT NED Administrative Procedure	Title: Significant Quality Problem Reporting and Corrective Action	No. 5.2 Page 1 of 5 Date: 03/26/91 Revision A
Reviewed by: *[signature]*	Approved: *[signature]*	

1.0 PURPOSE AND SCOPE

1.1 The purpose and scope of this Administrative Procedure (AP) is to establish the policy, requirements, and responsibilities for measures to identify, resolve, and track significant quality problems. This procedure satisfies the applicable requirements of the MIT NED QAPP, Section 16.0.

2.0 POLICY

2.1 Significant quality problems shall be identified by the process of evaluation of written submittals of quality documentation and/or by the review and evaluation of Audit Reports, Inspection Reports, Nonconformance Reports, etc.

2.2 Significant quality problems shall be formally identified and resolved so that repetition is minimized. Evaluation criteria for significant quality problems are the following:

A. Failure to establish, implement, and comply with appropriate requirements, QA Plans, and implementing procedures

B. Significant deficiencies in administrative and technical documentation which were not detected and corrected during formal reviews and which could render the quality of the items and activities either indeterminate or unacceptable

C. Continuing or repetitive procedural deviation, nonconformance, or noncompliance, and the failure of responsible organizations to provide proper direction, overview, and correction

D. Significant deficiencies in design and/or instruction for items which were detected after formal verification and acceptance and which, had they not been detected, could have had an adverse effect on safety

E. Failure of responsible organizations to take reasonably prompt and effective actions to correct findings of deficiencies noted during quality assurance audits or assessments

3.0 RESPONSIBILITIES AND PRACTICE

3.1	MIT QA Coordinator	1.	Ensures that when a potential significant quality problem is identified, a Graduate Research Assistant is assigned to initiate, monitor, and close a Corrective Action Report (CAR) (Appendix A).
3.2	Graduate Research Assistant	1.	Completes Section I of the CAR, including identification of root cause. Obtains concurrence of the MIT QA Coordinator on the

applicability of the quality concerns as a significant quality problem, and obtains CAR number, as applicable, from MIT QA Coordinator.

3.3 MIT QA Coordinator

1. Evaluates quality related concerns to determine if significant quality problem status applies.

2. Maintains Corrective Action Log and issues CARs. Issuance numbers shall be recorded in the log.

3. Maintains CAR files which include original CAR, current status, and related correspondence.

4. Transmits copy of the CAR to the MIT Principle Investigator.

5. Transmits the original CAR to the Graduate Research Assistant.

3.4 Graduate Research Assistant

1. Prepares proposed corrective actions to mitigate the problem identified in the CAR.

2. Transmits the original CAR to the MIT Principle Investigator and a copy to the MIT QA Coordinator.

3.5 MIT Principle Investigator

1. Reviews and approves the proposed corrective actions.

2. Ensures the following actions, as a minimum, be taken:

   A. Remedy of specific condition or problem

   B. Determination and documentation of root causes

   C. Review, implementation, monitoring, and revision of corrective actions as necessary

3.6 MIT QA Coordinator

1. Reviews and concurs with the proposed corrective actions.

2. Evaluates effectiveness of response and of corrective action.

3. Tracks corrective actions to completion.

3.7	Graduate Research Assistant	1.	Ensures the timely implementation and effectiveness of the completed corrective actions.
		2.	Indicates closure of the CAR by signing the "CAR Actions Completed and Closed" block.
3.8	MIT QA Coordinator	1.	Verifies the timely implementation and effectiveness of corrective actions.
		2.	Indicates closure of the CAR by signing the "Corrective Action Acceptance" block.
3.9	MIT Principle Investigator	1.	Indicates closure of the CAR by signing the "Closure of CAR Approved" block.
		2.	Transmits original closed CARs to the MIT QA Coordinator and a copy to the Graduate Research Assistant.
3.10	MIT QA Coordinator	1.	Completes entry in CAR Log.
		2.	Ensures that the CAR is retained as a QA record in accordance with AP 3.4, Records Management.

4.0 <u>DEFINITIONS</u>

4.1 <u>Significant Quality Problem</u>: a condition adverse to quality which, if not corrected, could have a serious effect on safety or other program objectives.

5.0 <u>REFERENCES</u>

The following documents were used to compile this AP:

5.1 SNL CSDP PD 5.2, Significant Quality Problem Reporting and Corrective Action

5.2 MIT NED QAPP

5.3 MIT NED AP 3.4, Records Management

6.0 <u>RECORDS</u>

6.1 The completed CAR and associated documentation are QA records and shall be maintained in accordance with AP 3.4, Records Management.

7.0 APPENDICES

7.1 Appendix A, MIT NED Corrective Action Report Form

APPENDIX A

MIT NED CORRECTIVE ACTION REPORT

To: ______________________ CAR No. __________

From: ______________________ Date: ___/___/___

Section I - Statement of Problem

CAR by: ______________________ Date: ___/___/___

Reviewed by: ______________________ Date: ___/___/___
MIT QA Coordinator

Section II - Discrepancy Response

Please indicate cause of problem and corrective action below. Sign and date as indicated. Return to sender by ___/___/___

Cause:

Action to correct observed discrepancy:

Corrective action to prevent recurrence:

Analysis by: ______________________ Date: ___/___/___

Committed by: ______________________ Date: ___/___/___

Section III - Evaluation of Response

Evaluation by: ______________________ Date: ___/___/___
Graduate Research Assistant

Reviewed by: ______________________ Date: ___/___/___
MIT QA Coordinator

Reviewed by: ______________________ Date: ___/___/___
MIT Principle Investigator

Section IV - Closure

CAR actions completed and closed: ______________________ Date: ___/___/___
Graduate Research Assistant

Corrective action acceptance: ______________________ Date: ___/___/___
MIT QA Coordinator

Closure CAR approved: ______________________ Date: ___/___/___
MIT Principle Investigator

NOTE: If more space is required, attach additional sheets.

1.0 PURPOSE AND SCOPE

1.1 The purpose and scope of this Administrative Procedure (AP) is to establish the policy, requirements, and responsibilities for scheduling, planning, conducting, and documenting quality audits for the MIT NED. This procedure satisfies the applicable requirements of the MIT NED QAPP, Section 18.0.

2.0 POLICY

2.1 This procedure specifies a system of planned, periodic audits to provide an objective evaluation of quality related practices, procedures, instructions, activities, and items, including the review of documents and records to ensure that the QA program is effective and properly implemented. This procedure applies to MIT NED activities. This procedure does not address qualification or certification of audit personnel, which are covered in AP 5.5, Auditor/Lead Auditor Qualification and Certification.

3.0 RESPONSIBILITIES AND PRACTICE

3.1 Planning and Scheduling

3.1.1 The MIT QA Coordinator will generate an audit schedule of external and internal audits annually. The audits and their performance sequence and timing will be based on the status and importance of the activities as they relate to the program. The audits will be scheduled in a manner that provides coverage of and coordination with ongoing program activities and shall be initiated early enough to assure effective QA. All elements of the QAPP will be scheduled to be audited at least annually. Elements to be audited may be scheduled throughout the year and performed on a continuous basis.

3.1.2 As a minimum, the annual Audit Schedule will include the following information:

A. Dates of audits

B. Activities to be audited

C. Quality level of work being performed

D. The requirements for which the activities are to be audited

E. The unique Audit Designator

3.2 Individual Audit Plans

3.2.1 For each audit, the MIT QA Coordinator or the Lead Auditor will prepare an Audit Plan, similar to Appendix A. The plan will be prepared as early in life of the activity as practical, shall be used throughout the audit, and will identify:

A. The organization to be audited
B. The requirements and documents to be audited against
C. The scope of the audit
D. Activities to be audited
E. The audit team
F. The personnel to be notified
G. The general schedule of the audit (planning through reporting)
H. The date(s) of the audit
I. The procedure or checklist used

3.2.2 The MIT QA Coordinator will approve each individual Audit Plan prior to its implementation.

3.3 Preparation for Audits

3.3.1 The MIT QA Coordinator will select certified Auditors to perform audits who are independent of the activity to be audited. The Auditors will be certified as qualified in accordance with AP 5.5, Auditor/Lead Auditor Qualification and Certification.

3.3.2 The Lead Auditor will develop or cause to be developed, an audit Checklist in a format similar to Appendix B. The checklist will include a review of corrective actions specified as a result of previous audits of the organization.

3.3.3 The MIT QA Coordinator will establish an Audit Designator for the audit. This will be an alphanumeric designation which uniquely identifies the audit.

3.3.4 The MIT QA Coordinator will notify the Graduate Research Assistant to be audited prior to the scheduled dates of the audit. The notification letter will include a copy of the Audit Plan and also indicate the general schedule desired for the audit visit. This would include any particular facilities or equipment needed. The audit checklist may be included in the notification letter.

3.4 Performance of the Audit

3.4.1 The audit team will hold an opening meeting with the audited personnel to review the audit plan and schedule.

3.4.2 The elements that have been selected for the audit shall be evaluated by the audit team against the specified requirements. The Lead Auditor may deviate from the audit plan to broaden the investigation when findings raise further questions or to delete unimportant activities. These deviations are to be annotated in the Checklist.

3.4.3 Audit personnel will document the results of their audit activities on the audit checklist(s). Conditions that require prompt corrective action will be reported immediately to the audited personnel.

3.4.4 The close-out meeting should occur immediately after the audit to provide the audited personnel an oral report of findings and observations. At this time, the lead auditor and the audited personnel should agree that the findings are factual.

3.5 <u>Reporting</u>

3.5.1 The audit report is to be written by the Lead Auditor/Audit Team and signed by the Lead Auditor and the MIT QA Coordinator. The audit report will be issued within 30 calendar days of the audit and distributed to:

1. MIT QA Coordinator
2. MIT Principle Investigator
3. Audited Personnel

The audit report is to include the following:

A. Executive summary of conclusions and significant results for management attention. This summary will indicate unsatisfactory results in the areas audited as well as exemplary practice

B. Audit scope and identification of the audit team

C. Identification of the personnel contacted during the audit

D. A summary of the audit results, including a statement of the adequacy and effectiveness of the QA program elements audited

E. A description of each reported finding and observation in sufficient detail to enable corrective action to be taken by the audited personnel. An Audit Finding/Observation Report (Appendix C) for each finding and observation shall be attached to the audit report.

3.5.2 The audit report shall require the audited personnel:

A. Investigate the findings and observations

B. Devise and schedule corrective actions

C. Provide a written response specifying and scheduling corrective actions and indicating measures taken to prevent recurrence.

The written response shall be submitted to the MIT Principle Investigator and to the MIT QA Coordinator within thirty (30) calendar days of the receipt of the audit report.

3.6 Follow-up

3.6.1 The MIT QA Coordinator will evaluate the adequacy of the auditee's corrective action. If the corrective action is inadequate, further action will be requested.

3.6.2 Follow-up action will be taken within 30 calendar days of notification by observing objective evidence to verify that corrective action has been accomplished as scheduled. The MIT QA Coordinator will maintain a tracking system which indicates the extent of completion of the audit and close-out of findings.

3.6.3 After the corrective action has been verified, the MIT QA Coordinator will issue a close-out letter stating that the corrective action is adequate and the audit is closed-out.

4.0 DEFINITIONS

4.1 Audit: a planned and documented activity performed to determine by investigation, examination, or evaluation of objective evidence the adequacy of and compliance with established procedures, codes, standards, instructions, drawings, and other applicable requirements, and the effectiveness of implementation. An audit should not be confused with inspection activities performed for the sole purpose of process control or product acceptance.

4.2 Corrective Action: measures taken to rectify conditions that are adverse to quality and, where necessary, to preclude repetition.

4.3 Finding: a statement of fact regarding noncompliance with established policies, procedures, instructions, drawings, or other applicable requirements. (Findings require a documented response specifying corrective action and verification of its accomplishments.)

4.4 Observation: a statement of opinion regarding a potential quality problem, quality assurance weakness or practice which could lead to a finding if not corrected. (Observations require a documented response specifying corrective action.)

4.5 Recommendation: a statement of opinion related to adequacy of compliance with quality assurance requirements, effectiveness of quality assurance program implementation and areas of improvement which should be considered. (A recommendation does not require a documented response.)

5.0 REFERENCES

The following documents were used to compile this AP:

5.1 SNL CSDP PD 5.3, Quality Audit

5.2 MIT NED QAPP

5.3 MIT NED AP 3.4, Records Management

5.4 MIT NED AP 5.5, Auditor/Lead Auditor Qualification and Certification

5.5 MIT NED AP 5.6, Quality Program Levels of Effort

6.0 RECORDS

6.1 Audit schedule and revisions, audit plans, audit reports, written replies, and the record of completion of corrective action, and close-out of the audit are QA records and shall be maintained in accordance with AP 3.4, Records Management.

7.0 APPENDICES

7.1 Appendix A, MIT NED QA Audit Plan

7.2 Appendix B, MIT NED QA Audit Checklist

7.3 Appendix C, MIT NED Audit Finding/Observation Report Form

APPENDIX A

MIT NED QA AUDIT PLAN

____
Audit Designator

Organization to be Audited:

Applicable Requirement Documents:

Audit Scope:

Activities to be Audited:

General Audit Schedule:

- **Planning and Preparation -**
- **Notification to Auditee -**
- **Date(s) of Audit Performance -**
- **Issue Report -**

Audit Team:

Personnel or Organization to be Notified:

Procedure or Checklist to be Used:

Signature: ______________________________ **Date:** ____/____/____
Lead Auditor

Approved: ______________________________ **Date:** ____/____/____
MIT QA Coordinator

APPENDIX B

MIT NED QA AUDIT CHECKLIST

Audit Designator: ________________ Auditor(s): ________________

Criteria Audited: ____________

Requirements Document(s) and Revision(s): ____________________

Organization Audited: ________________ Personnel Contacted: ________________

Requirements	Sat.	Unsat.	Remarks

APPENDIX C

MIT NED AUDIT FINDING/OBSERVATION REPORT

1. AUDITED ORGANIZATION: ____________ 2. DISCUSSED WITH: ____________ 3. AFOR NO.: ____________

4. AUDITOR(S): ____________ 5. FINDING [ ] OBSERVATION [ ] 6. PAGE ___ OF ___

7. RESPONSE DUE DATE: ___/___/___

8. REQUIREMENT: ____________

9. FINDING/OBSERVATION: ____________

SEE REVERSE SIDE FOR INSTRUCTIONS

10. CAUSE: ____________

11. REMEDIAL CORRECTIVE ACTION AND EFFECTIVE DATE: ____________

12. ACTION TO PRECLUDE RECURRENCE: ____________

13. SIGNIFICANT CONDITION ADVERSE TO QUALITY: NO [ ] YES [ ]
IF YES, CAR NO.: ____________ ISSUED: NO [ ] YES [ ]

14. COMMITMENT DATE AND RESPONSIBILITY FOR CORRECTIVE ACTION, INCLUDING CONFIRMATION TO MIT QA COORDINATOR: ____________

15. RESPONSIBLE PERSONNEL AND DATE: ____________

16. EVALUATION OF CORRECTIVE ACTION STATEMENT: SATISFACTORY [ ] UNSATISFACTORY [ ]

17. MIT QA COORDINATOR AND DATE: ____________

18. VERIFICATION OF ACTION TAKEN: SATISFACTORY [ ] UNSATISFACTORY [ ]

19. MIT QA COORDINATOR AND DATE: ____________

APPENDIX C (continued)

MIT NED AUDIT FINDING/OBSERVATION REPORT

Instructions

STEP 1: Root Cause Determination

Be specific in identifying the root cause of the problem. Document response in Space 10.

STEP 2: Remedial Corrective Action and Effective Date

Document actions taken to correct the specific problems identified. Be specific, record items corrected and how corrected. Record in Space 11. Investigate other similar areas/items that might have similar problems. Document this activity, identify items reviewed and items corrected. Evaluate the problem impact on complete work. State result in Space 11.

STEP 3: Actions to Preclude Recurrence

Identify what actions have been and/or will be taken to preclude recurrence. Record specifics in Space 12.

STEP 4: Determine significance of problem and need for a CAR to ensure appropriate action. Record in Space 13.

STEP 5: Commitment Date and Responsibility for Corrective Action, including Confirmation to MIT QA Coordinator

Identify who is responsible for the steps above and the date each action is to be completed; record the latest date identified for corrective action in Space 14. The identified individual is responsible for follow up to complete required actions, and for findings, to confirm and provide objective evidence to the MIT QA Coordinator that corrective action has been accomplished as committed. Sign and date in Space 15.

STEP 6: Transmittal

Return this report to the MIT QA Coordinator.

NOTE: Use additional sheets for continuation of information from the front page.

1.0 PURPOSE AND SCOPE

1.1 The purpose and scope of this Administrative Procedure (AP) is to describe the policy, requirements, responsibilities, and applicability for the initiation and lifting of a stop work request on MIT NED activities. This procedure satisfies the applicable requirements of the MIT NED QAPP, Section 1.0.

2.0 POLICY

2.1 A Stop Work Request (SWR) letter shall be initiated by MIT QA Coordinator when conditions warrant and when all other avenues of resolution have been exhausted.

3.0 RESPONSIBILITIES AND PRACTICE

3.1 MIT NED Personnel

1. Contact the MIT QA Coordinator when a significant problem possibly warranting a Stop Work Request is identified.

3.2 MIT QA Coordinator

1. Determines whether the problem can be resolved in accordance with the guidelines and direction of existing APs such as AP 5.8, Control of Nonconforming Items; AP 5.2, Significant Quality Problem Reporting and Corrective Action, or AP 2.10, Inspection. If so, initiates corrective action in accordance with procedures.

2. If existing programs and procedures are not satisfactory to resolve the problem, determines whether the problem can be resolved through immediate interaction with involved parties. If so, promptly resolves the problem and documents corrective action.

3. If neither Steps 1 or 2 resolves the problem, determines whether a Stop Work Request is warranted, based on the definition in Section 4.0 of this procedure.

   a. If a SWR is not applicable, resolves the problem with the Graduate Research Assistant or escalates until resolved.

b. If an SWR is applicable, completes the applicable portions of the SWR.

4. Submits SWR to Graduate Research Assistant.

5. Ensures, through tagging, segregating or other means, that the problem represents no threat to personnel, structures or the environment while resolution is pending.

3.3 Graduate Research Assistant (RA)

1. Evaluates the SWR for applicability.

2. If the Graduate RA concurs with the SWR, directs the stoppage of work (if not already stopped) and completes any applicable portion of the SWR not already completed.

a. Assigns responsibilities to designated personnel for corrective actions.

b. Distributes the SWR letter as follows:

(1) MIT Principle Investigator

(2) MIT QA Coordinator

c. Maintains a log of SWR letters

d. Tracks corrective action.

3. If the Graduate RA does not concur with the SWR:

a. Documents the justification for not concurring.

b. Provides an action plan for correcting the problem.

c. Obtains the concurrence of the MIT QA Coordinator for items a and b.

3.4 MIT QA Coordinator

1. Concurs with the justification for canceling the SWR and with the corrective action plan or escalates the problem until resolved.

3.5 Designated Personnel

1. Implement corrective actions as directed on SWR and notifies the Graduate RA, in writing, when actions are complete.

3.6 MIT Principle Investigator

1. Reviews, concurs, and verifies corrective action.
2. May request the assistance of the MIT QA Coordinator for verification of corrective action.
3. Lifts the stop work verbally and in writing and advises the MIT QA Coordinator of the lifting of stop work.

3.7 MIT QA Coordinator

1. Verifies corrective action if requested and documents same.
2. Removes any tags applied and releases the item for service, if applicable.
3. Distributes all SWR correspondence as follows:
   a. Graduate RA
   b. MIT Principle Investigator
4. Ensures that the SWR letter and associated documentation is retained as a QA record.

4.0 <u>DEFINITIONS</u>

4.1 <u>Stop Work Request</u>

A Stop Work Request (SWR) is a letter issued for activities not in substantial compliance with QA program requirements or activities for which corrective action is not implemented in a timely manner. Generally, an SWR should not be issued unless other appropriate means have been exhausted. However, the MIT QA coordinator or other responsible personnel may elect to issue an SWR as a first means to correct an unsatisfactory condition if circumstances warrant. An SWR shall be lifted by the MIT Principle Investigator. An SWR letter shall contain the following:

a. An SWR number indicating the year and the chronological number of the SWR (e.g., 1990-3 is the third SWR issued in 1990).

b. An exact description of the affected program/project/task element and of the work being stopped.

c. The reason for the SWR.

d. The conditions required before the SWR will be lifted.

e. A statement that it is the addressee's responsibility to assure that work is stopped and corrective action is taken in a timely manner.

f. A request that the addressee notify the MIT QA Coordinator in writing of the corrective actions to be taken for acceptance or resolution.

g. A request that the personnel notify the MIT Principle Investigator in writing when the accepted corrective action has been completed who in turn notifies the MIT QA Coordinator in writing.

5.0 REFERENCES

The following documents were used to compile this AP:

5.1 SNL CSDP PD 5.4, Stop Work Request

5.2 MIT NED QAPP

5.3 MIT NED AP 2.10, Significant Quality Problem Reporting and Corrective Action

5.4 MIT NED AP 3.4, Records Management

5.5 MIT NED AP 5.8, Control of Nonconforming Items

6.0 RECORDS

6.1 The SWR letter and associated documentation are QA records and shall be maintained in accordance with AP 3.4, Records Management.

7.0 APPENDICES

None.

1.0 **PURPOSE AND SCOPE**

1.1 The purpose and scope of this Administrative Procedure (AP) is to establish the minimum qualification requirements for personnel who perform or participate in quality assurance audits as an Auditor or Lead Auditor. This procedure satisfies the applicable requirements of the MIT NED QAPP, Section 2.0 and 18.0.

2.0 **POLICY**

2.1 This procedure specifies the qualification and certification requirements for personnel who perform or participate in quality assurance audits in the role of Auditor or Lead Auditor.

3.0 **RESPONSIBILITIES AND PRACTICE**

3.1 **Qualification Requirements**

3.1.1 **Qualification of Auditors**

3.1.1.1 The prospective Auditor shall have sufficient, appropriate education and experience that a minimum of five (5) credits using the following scoring system are accumulated and documented in the Auditor/Lead Auditor Qualification Record (Appendix A): (See Appendix B for explanation of credits).

A. Education: four (4) Credits Maximum

B. Experience: nine (9) Credits Maximum

C. Other Credentials of Professional Competence: two (2) Credits Maximum

D. Rights of Management: two (2) Credits Maximum

3.1.2 **Qualification of Lead Auditors**

3.1.2.1 The prospective Lead Auditor shall have sufficient, appropriate education and experience that a minimum of ten (10) credits using the following scoring system are accumulated and documented in the Auditor/Lead Auditor Qualification Record (Appendix A): (See Appendix B for explanation of credits).

A. Education: four (4) Credits Maximum

B. Experience: nine (9) Credits Maximum

C. Other Credentials of Professional Competence: two (2) Credits Maximum

D. Rights of Management: two (2) Credits Maximum

3.1.3 The Auditor/Lead Auditor Qualification Record shall be certified by the MIT QA Coordinator and approved by the MIT Principle Investigator.

4.0 DEFINITIONS

4.1 Auditor: an individual who performs any portion of an audit, excluding Lead Auditor functions.

4.2 Lead Auditor: an individual specifically qualified to organize and direct an audit, to report audit findings, and to evaluate corrective action.

5.0 REFERENCES

The following documents were used to compile this AP:

5.1 SNL CSDP PD 5.5, Auditor/Lead Auditor Qualification and Certification

5.2 MIT NED QAPP

5.3 MIT NED AP 5.3, Quality Audit

5.4 MIT NED AP 3.4, Records Management

6.0 RECORDS

6.1 The Auditor/Lead Auditor Qualification Form, is a QA record and shall be maintained in accordance with AP 3.4, Records Management.

7.0 APPENDICES

7.1 Appendix A, MIT NED Auditor/Lead Auditor Qualification Form

7.2 Appendix B, Instructions for Qualification Points

APPENDIX A

MIT NED AUDITOR/LEAD AUDITOR QUALIFICATION FORM

Qualification for: Auditor [ ] Lead Auditor [ ]

Name: ____________________

Position: ____________________

QUALIFICATION POINT REQUIREMENTS		CREDITS
Education--University/Degree Date 1. Undergraduate Level 2. Graduate Level	4 Credits Max.	
Experience--Company/Dates Technical (0-5 credits) and Nuclear industry (0-1 credit), or Quality Assurance (0-2 credits), or Auditing (0-4 credits)	9 Credits Max.	
Professional Accomplishment--Certificate/Date 1. P.E. 2. Society 3. Other	2 Credits Max.	
Management--Justification/Evaluator/Date Explain: Evaluated by: ____________________ Title: ____________ Date: __/__/__	2 Credits Max.	

Total Credits: ________

Certified by: ____________________ Date: __/__/__

Approved by: ____________________ Date: __/__/__

APPENDIX B

INSTRUCTIONS FOR QUALIFICATION POINTS

- EDUCATION (Highest degree only) for an accredited institution	MAXIMUM 4 CREDITS
Associate Degree	1
Associate Degree in Engineering, Physical Sciences, Mathematics, or Quality Assurance	2
Bachelor Degree	2
Bachelor Degree in Engineering, Physical Sciences, Mathematics, or Quality Assurance	3
Master Degree in Engineering, Physical Sciences, Business Management, or Quality Assurance - additional credit	1
- EXPERIENCE	MAXIMUM 9 CREDITS
Technical Experience in Engineering, Manufacturing, Construction, Operation, or Maintenance - One Credit for Each Year	5
Nuclear Industry* - including either Nuclear Power Industry, Navy Nuclear experience or Nuclear Weapons complex experience	1
Quality Assurance*	2
Auditing*	3
- PROFESSIONAL CERTIFICATION in Engineering, Science, or Quality Assurance	MAXIMUM 2 CREDITS
Professional Engineer (Registered by State Agency)	2
National Professional or Technical Society	2
Other Certification	1
- RIGHTS OF MANAGEMENT**	MAXIMUM 2 CREDITS

*Score one (1) additional credit if two (2) or more years are nuclear industry experience.

**Based on performance factors such as leadership, sound judgement, maturity, analytical ability, tenacity, and past performance

MIT NED Administrative Procedure	Title: Quality Program Levels of Efforts	No. 5.6 Page 1 of 9 Date: 03/27/91 Revision: A
Reviewed by: Phyllis M. Lord	Approved: Neil E. Todreas	

1.0 PURPOSE AND SCOPE

1.1 The purpose and scope of this Administrative Procedure (AP) is to outline the tri-level Quality Assurance system to assure the application of the appropriate level of QA to various tasks. This procedure satisfies the applicable requirements of the MIT NED QAPP, Section 2.0.

2.0 POLICY

2.1 This procedure provides control over MIT NED activities that affect quality and those activities that could have an impact on public radiological health and safety.

3.0 RESPONSIBILITIES AND PRACTICE

3.1 Establishing QA Level of a Task

3.1.1 The Graduate Research Assistant, in consultation with and approval of the MIT QA Coordinator, and using the guidance of Appendices A and B, completes Appendix C and assigns each task a QA Level.

3.2 Determining Extent of Controls

3.2.1 The Graduate Research Assistant determines the extent of the QA program efforts to be applied to a task using the guidance in Appendices A and B.

3.2.2 Decision shall be made with the assistance and concurrence of the MIT QA Coordinator and MIT Principle Investigator.

3.3 Applying QA Levels to Procurement Actions

3.3.1 Based on the assigned QA Level, quality requirements and controls are applied to procurement actions in accordance with AP 3.2, Preparation and Control of Procurement Documents.

4.0 DEFINITIONS

4.1 Tri-Level Classification System: a classification system used to identify the relative degree of risk to public radiological health and safety should be an item or task not be adequately controlled.

4.2 Quality Level 1 (QL1): Items or activities assigned this classification are ones where an omission, error, or failure could directly impact public radiological health and safety. From a mechanistic perspective, if an adverse radiological effect (exceeding regulatory limits) may be initiated by an omission, error, or failure of an item or activity, then that item or activity must be classified as QL1. The determination of which initiating events involving items and activities that might result in the above effects must be made on a case-by-case basis at the time of classification. Criticality events and failure of containment and shielding are among the events that require analysis. QL1 items and activities shall meet the basic and supplemental requirements of ANSI/ASME NQA-1.

4.3 Quality Level 2 (QL2): Items and activities assigned this classification are ones, under the direct control of the OCRWM CSDP, where an omission, error, or failure could lead to circumstances that could require QL1 items or activities to perform their safety-related function. Therefore, an indirect relationship exists between QL2 items and activities and adverse radiological effects to public health and safety. An example might be the brakes on a trailer carrying a nuclear spent fuel cask. A failure of the brakes might precipitate an accident which in turn could challenge the cask containment. QL2 items and activities shall meet the basic and selected supplemental requirements of ANSI/ASME NQA-1.

4.4 Quality Level 3 (QL3): QL3 is for assignment to OCRWM activities selectively chosen because of special programmatic importance other than radiological safety. These include mission-oriented activities controlled by DOE orders and procedures which reflect good technical management practices for the assurance of quality. Additionally, NQA-1 requirements may be selectively applied as determined by line management.

5.0 REFERENCES

The following documents were used to compile this AP:

5.1 SNL CSDP PD 5.6, Quality Program Levels of Effort

5.2 MIT NED QAPP

5.3 MIT NED AP 3.2, Preparation and Control of Procurement Documents

5.4 MIT NED AP 3.4, Records Management

6.0 RECORDS

6.1 The Completed Quality Level Assignment Checklist is a QA record and shall be maintained in accordance with AP 3.4, Records Management.

7.0 APPENDICES

7.1 Appendix A, Quality Level Guidance

7.2 Appendix B, Quality Level Requirements

7.3 Appendix C, Quality Level Assignment Checklist

APPENDIX A

QUALITY LEVEL GUIDANCE

This appendix gives guidelines to be followed by MIT NED participants to meet the Quality Levels 1, 2, and 3 requirements.

Quality Level 1:

1. Design shall be based on the appropriate codes or standards.
2. Design verification shall be achieved by prototype testing and/or formal design review.
3. Procurement documentation for items or services shall specify that only vendors on approved vendors' list be used.
4. Suppliers and subtier suppliers shall have a QA Program based on Title 10 Code of Federal Regulations Part 71 Subpart H, ANSI/ASME NQA-1, and other applicable contract requirements.
5. Manufacturing planning shall specify traceability of raw materials.
6. Special processes shall be conducted by certified personnel and procedures.
7. Verification planning shall require qualified personnel in accordance with SNT-TC-1A, Section IX of ASME Boiler and Pressure Vessel Code, or other applicable standards.
8. All verifications at prescribed hold points shall be performed by independent personnel.

Quality Level 2:

1. Design shall be based on the appropriate codes and standards.
2. Design verification may be achieved through the use of calculations and/or computer codes.
3. Procurement of items or services shall be from a qualified vendor.
4. Suppliers and subtier suppliers shall have a QA Program commensurate with the items or services rendered.
5. A Certification of Compliance is acceptable for raw materials.
6. Special processes shall be conducted by certified personnel and procedures.
7. Verification activities shall be performed by personnel qualified to the appropriate codes, standards, or procedures.

APPENDIX A (continued)

QUALITY LEVEL GUIDANCE

8. Independent verification shall be performed at all verification or testing hold points.

9. Program studies/activities shall require:

   - Documented process
   - Independent verification of process
   - Validation of computer codes
   - Independent review of data/report.

Quality Level 3:

1. Items may be purchased from a catalog.

2. Items received and used shall be traceable to purchase document.

3. Items and services may be purchased as appropriate to specified requirement on procurement documents.

4. Suppliers and subtier suppliers need to have a QA Program commensurate with the item or services rendered.

5. Certification of Compliance is acceptable to verify compliance to specified requirements.

6. Program studies shall require documented process.

APPENDIX B

QUALITY LEVEL REQUIREMENTS

A. QA Level 3 items and activities will be controlled by the necessary and appropriate QA Program requirements selectively applied by management. QA Level 3 activity designation requires:

1. A documented, adaptable management plan that includes identification of applicable quality management requirements and/or supplemental procedural controls as determined by the MIT Principle Investigator

2. Assignment of responsibility to personnel for achieving and verifying quality

3. Indoctrination and training of personnel in the role and function of procedures and supplemental requirements applicable to the Level 3 activities and their importance to the quality objectives of the MIT NED

4. Verification of procedural adequacy and effectiveness in achieving quality

5. Reporting separate from QA Level 2 and QA Level 1

B. QA Level 2 items and activities shall meet the basic and selected supplemental requirements of NQA-1. In addition to the technical management requirements and procedure controls for Quality Level 3 activities, QA Level 2 activity designation requires:

1. A formal, documented, and adaptable QA plan in compliance with QA policies and requirement

2. Compliance with NRC regulatory QA requirements on a case-by-case basis

3. Reporting separate from QA Level 3

C. QA Level 1 items and activities shall meet the basic and supplemental requirements of ANSI/ASME NQA-1. In addition to the formal QA Program requirements and procedural controls applicable to Quality Level 2 activities, QA Level 1 activity designation requires:

1. Identification and listing (Q List) of those technical activities covered by QA Level 1 QA programs

2. Compliance with applicable NRC certification and regulatory QA requirements, review plans, generic technical positions, and guidance

3. Reporting separate from QA Level 3

APPENDIX C (page 1 of 4)

QUALITY LEVEL ASSIGNMENT CHECKLIST

Project Contract No. ________________ Contract Organization ______________

MIT NED Participants ____

____

Project Title ____

____

Q-Level Assignment Criteria: The definitions of quality level are given in AP 5.6, Quality Program Levels of Effort.

For convenience, the Quality Level definitions are:

Quality Level 1 (QL1): Items or activities assigned this classification are ones where an omission, error, or failure could directly impact public radiological health and safety. From a mechanistic perspective, if an adverse radiological effect (exceeding regulatory limits) may be initiated by an omission, error, or failure of an item or activity, then that item or activity must be classified as QL1. The determination of which initiating events involving items and activities that might result in the above effects must be made on a case-by-case basis at the time of classification. Criticality events and failure of containment and shielding are among the events that require analysis. QL1 items and activities shall meet the basic and supplemental requirements of ANSI/ASME NQA-1.

Quality Level 2 (QL2): Items and activities assigned this classification are ones, under the direct control of the OCRWM CSDP, where an omission, error, or failure could lead to circumstances that could require QL1 items or activities to perform their safety-related function. Therefore, an indirect relationship exists between QL2 items and activities and adverse radiological effects to public health and safety. An example might be the brakes on a trailer carrying a nuclear spent fuel cask. A failure of the brakes might precipitate an accident which in turn could challenge the cask containment. QL2 items and activities shall meet the basic and selected supplemental requirements of ANSI/ASME NQA-1.

Quality Level 3 (QL3): QL3 is for assignment to OCRWM activities selectively chosen because of special programmatic importance other than radiological safety. These include mission-oriented activities controlled by DOE orders and procedures which reflect good technical management practices for the assurance of quality. Additionally, NQA-1 requirements may be selectively applied as determined by line management.

APPENDIX C (page 2 of 4)

QUALITY LEVEL ASSIGNMENT CHECKLIST

The key to defining appropriate quality levels for each task is to use a logic network to identify how a "failure" in the task (or subtask) or erroneous results can impact one of the cask safety functions; criticality control, shielding, containment, or heat removal. An activity that can have a "direct" (QL1) impact on a cask safety function is essentially a dominant, single failure mode; i.e., if an error or failure occurs, a cask safety function is directly compromised. In a "fault tree" or "event tree," a set of "directly" affecting events will intersect through an "or" gate; i.e., each event can alone have a major impact on safety.

On the other hand a set of "indirect" events or activities requiring QL2 quality control will intersect through an "and" gate in a failure mode logic network. That is, an error or failure occurs in one or more other independent tasks or activities.

Finally, QL3 requirements are specified for all other activities. For other programs, the definition above requires QL3 quality control for all activities which have some impact to health and safety.

The appropriate quality level of a task can be determined by addressing questions related to the task's impact on health and safety, program direction, budget or schedule, or the functional design basis and subsequent performance of criticality, shielding, containment, or thermal safety features of a cask. The questions may be applied to any task category such as experimental, computational, safety assessments, software development, testing, data acquisition, reporting, etc. All questions will not necessarily apply to every task. An affirmative reply in the highest quality category determines the QA requirements for the task.

<u>Q-Level 1</u>:

		<u>Yes</u>	<u>No</u>
1.	Is the task on the SNL CSDP Q-list?	____	____
2.	Has DOE specified QL-1 QA requirements in program documents for this task?	____	____
3.	Could erroneous task results directly and independently result in exposure to radiation or release of radioactive materials (RAM) in excess of the limits specified in 10CFR71 during normal or accident conditions or transport?	____	____
4.	Do the results of this task directly determine the design criterion or functional design basis of a Q-list item? (Such as criticality, shielding, containment or heat management effectiveness?)	____	____
5.	Are QL1 QA requirements appropriate for this task for other reasons?	____	____

APPENDIX C (page 3 of 4)

QUALITY LEVEL ASSIGNMENT CHECKLIST

Q-Level 2:

		Yes	No
1.	Could failure or malfunction of an item or activity associated with this task have a potentially significant impact on worker or public radiological or nonradiological health and safety?	____	____
2.	Would loss of task data or records result in significant program costs or schedule delays?	____	____
3.	Will the task results support critical (SNL/DOE) program decisions such as which cask designs will be developed, fabricated, or procured for fleet use?	____	____
4.	Could erroneous task results, in combination with abnormal factors, result in reduced reliability of the criticality, shielding, containment, or heat removal capabilities of a cask?	____	____
5.	Does this task support the development of a design "standard" for a cask safety feature?	____	____
6.	Are QL2 QA requirements for this task appropriate for other reasons?	____	____

Q-Level 3:

		Yes	No
1.	Does the task support the DOE CSDP program?	____	____
2.	Does the task have a potential impact on public health and safety?	____	____
3.	Will the task involve validation of theoretical or analytical models relating to cask design?	____	____
4.	Does the task involve feasibility assessments of advanced technological applications with the results intended to impact CSDP program direction?	____	____
5.	Does the task involve parametric or sensitivity analyses that will be used to focus more detailed and expensive efforts in the future?	____	____

APPENDIX C (page 4 of 4)

QUALITY LEVEL ASSIGNMENT CHECKLIST

		Yes	No
6.	Would loss of task data and records or loss of task "memory" in the event of personnel changeover jeopardize the ability to meet outstanding program milestones?	____	____
7.	Are QL3 task requirements appropriate for other reasons?	____	____

ASSIGNED TASK QUALITY LEVEL: ____________

Graduate Research Assistant ____________ Date

Approved MIT QA Coordinator ____________ Date

Approved MIT Principle Investigator ____________ Date

MIT NED Administrative Procedure	Title: Qualification of Inspection and Test Personnel	No. 5.7 Page 1 of 6 Date: 05/28/91 Revision: B
Reviewed by: Phyllis M. Lord	Approved: Neil Todreas	

1.0 PURPOSE AND SCOPE

1.1 The purpose and scope of this Administrative Procedure (AP) is to establish the policy, requirements, and responsibilities for the planning, implementation, and maintenance of a quality program relating to the qualification of inspection and test personnel. This procedure satisfies the applicable requirements of the MIT NED QAPP, Section 2.0, 9.0, 10.0 and 11.0.

2.0 POLICY

2.1 The MIT NED shall implement qualification of inspection and test personnel in accordance with the MIT NED QAPP.

3.0 RESPONSIBILITIES AND PRACTICE

3.1 Graduate Research Assistant

3.1.1 Certifies Level I and II personnel in accordance with the requirements of this AP.

3.1.2 Completes Appendix B, MIT NED Inspection and Test Personnel Certification Record, for the MIT NED personnel.

3.1.3 Specifies qualification levels for personnel designated in test procedures.

3.1.4 Ensures that personnel who perform inspection or testing are qualified according to Appendix A to perform their assigned activities.

3.2 MIT Principle Investigator

3.2.1 Ensures the overall effectiveness and implementation of this document.

3.2.2 Approves qualification levels designated on individual test and inspection personnel.

3.3 MIT QA Coordinator

3.3.1 Ensures certification of inspection and test personnel.

3.3.2 Ensures that records of inspection and test personnel qualification and certification are established and maintained.

4.0 DEFINITIONS

4.1 Certification: the act of determining, verifying, and attesting in writing to the qualification of personnel, processes, procedures, or items in accordance with specified requirements.

4.2 Inspection: examination or measurement to verify whether an item or activity conforms to specified requirements.

4.3 Inspection and Test Personnel: individuals who perform inspection and testing, including set-up, adjustment, and use of precision measuring equipment.

4.4 Qualified Individual: a person trained, indoctrinated, and practiced to a level of capability commensurate with the scope, complexity, or special nature of the job assignment.

4.5 Testing: an element of verification for the determination of the capability of an item to meet specified requirements by subjecting the item to a set of physical, chemical, environmental, or operating conditions. Testing may include nondestructive methods.

5.0 REFERENCES

The following documents were used to compile this AP:

5.1 SNL CSDP PD 5.7, Qualification of Inspection and Test Personnel

5.2 MIT NED QAPP

5.3 MIT NED AP 3.4, Records Management

6.0 RECORDS

6.1 Inspection and test personnel qualification and certification documents are QA records and shall be maintained in accordance with AP 3.4, Records Management.

7.0 APPENDICES

7.1 Appendix A, Requirements for the Qualification of Inspection and Test Personnel

7.2 Appendix B, MIT NED Inspection and Test Personnel Certification Record

APPENDIX A

REQUIREMENTS FOR THE QUALIFICATION OF INSPECTION AND TEST PERSONNEL

1.0 GENERAL

The following are the requirements for the qualification of personnel who perform inspection and testing.

2.0 FUNCTIONAL QUALIFICATIONS

Three levels of qualification shall be utilized depending on the complexity of the functions involved. The requirements for each level are limiting with regard to functional activities.

2.1 LEVEL I PERSONNEL CAPABILITIES

A Level I person shall be capable of performing and documenting the results of inspections or tests that are required to be performed in accordance with documented procedures and/or acceptance standards.

2.2 LEVEL II PERSONNEL CAPABILITIES

A Level II person shall have all of the capabilities of a Level I person for the inspection or test category or class in question. Additionally, a Level II person shall have demonstrated capabilities in planning inspections and tests; in setting up tests, including preparation and setup of related equipment, as appropriate; in supervising and certifying lower level personnel; and in evaluating the validity and acceptability of inspection and test results.

2.3 LEVEL III PERSONNEL CAPABILITIES

A Level III person shall have all the capabilities of a Level II person for the inspection, test category or class in question. In addition, the individual shall also be capable of evaluating the adequacy of specific programs used to train and certify inspection and test personnel whose qualifications are covered by this section.

3.0 EDUCATION AND EXPERIENCE QUALIFICATIONS

These education and experience requirements shall be considered with recognition that other factors commensurate with the scope, complexity, or special nature of the inspection or test activity may provide reasonable assurance that a person can competently perform a particular task (such as, demonstration capability testing).

3.1 LEVEL I EDUCATION AND EXPERIENCE REQUIREMENTS

- Two years of related experience; or
- High school graduation and six months of related experience; or
- Completion of college level work leading to an associate degree in a related discipline plus three months of related experience.

3.2 LEVEL II EDUCATION AND EXPERIENCE REQUIREMENTS

- One year of satisfactory performance as a Level I class; or
- High school graduation plus three years of related experience; or
- Completion of college work leading to an associate degree in a related discipline plus one year of related experience; or
- Graduation from a four-year college plus six months of related experience.

3.3 LEVEL III EDUCATION AND EXPERIENCE REQUIREMENTS

- Six years satisfactory performance as a Level II class; or
- High school graduation plus ten years of related experience; or
- Completion of college level work leading to an associate degree and seven years of related experience; or
- Graduation from a four-year college plus five years related experience.

4.0 CERTIFICATION

4.1 PERSONNEL SELECTION

Personnel selected to perform inspection and test activities shall have the experience or training commensurate with the scope of the activities.

4.2 INDOCTRINATION

Provisions shall be made for the indoctrination of personnel as to the technical objectives and procedures that are to be employed.

4.3 TRAINING

Training shall be provided with regard to the MIT NED QAPP and implementing procedures.

4.4 DETERMINATION OF INITIAL CAPABILITY

The capabilities of a candidate for certification shall be initially determined by a suitable evaluation of the candidate's education, experience, training, and capability demonstration.

4.5 CERTIFICATION OF QUALIFICATION

The qualification of personnel shall be certified in writing in an appropriate form, including the following information:

- Identification of person being certified
- Activities certified to perform
- Basis used for certification that includes such factors as:
    1. Education, experience, and training
    2. Results of capability demonstration
- Signature of Graduate Research Assistant and MIT Principle Investigator
- Dates of certification and certification expiration

APPENDIX B

MIT NED INSPECTION AND TEST PERSONNEL CERTIFICATION RECORD

NAME: ____________________

POSITION: ____________________

ACTIVITIES CERTIFIED TO PERFORM (include certified level):

____
____
____
____
____

BASIS FOR CERTIFICATION:

Education: ____________________
____
____
____
____

Experience: ____________________
____
____
____
____

Demonstration Capabilities: ____________________
____
____
____
____
____
____
____

DATE OF CERTIFICATION: ___/___/___ DATE CERTIFICATION EXPIRES: ___/___/___

Certified by: ____________________ Date: ___/___/___
Certified Graduate Research Assistant

Approved by: ____________________ Date: ___/___/___
MIT Principle Investigator

MIT NED Administrative Procedure	Title: Control of Nonconforming Items	No. 5.8 Page 1 of 5 Date: 05/28/91 Revision: B
Reviewed by: [signature]	Approved: [signature]	

1.0 PURPOSE AND SCOPE

1.1 The purpose and scope of this Administrative Procedure (AP) is to establish the policy, requirements, and responsibilities for the initiating, processing, dispositioning, and closing a Nonconformance Report (NCR). This procedure satisfies the applicable requirements of the MIT NED QAPP, Section 15.0.

2.0 POLICY

2.1 Nonconformance Reports shall be initiated for nonconforming items.

3.0 RESPONSIBILITIES AND PRACTICE

3.1 MIT NED Personnel

1. Take any immediate action to mitigate the consequences of the nonconformance.

2. Initiate an NCR (Appendix A) by completing all pertinent information describing the nonconformance; attach additional pages as necessary.

3. Forward the NCR to the Graduate Research Assistant.

3.2 Graduate Research Assistant

1. Reviews the NCR for validity.

A. If not valid, returns the NCR to the originator with an explanation and provides a copy of the NCR and explanation to the MIT QA Coordinator.

B. If valid, obtains an NCR number from the MIT QA Coordinator.

3.3 MIT QA Coordinator

1. Assigns NCR number and maintains a log to track the status of applicable corrective actions.

2. Accounts for voided NCRs.

3.4 Graduate Research Assistant

1. Ensures the placement of a Nonconformance Hold Tag (Appendix B) on the item or segregates the item from used if tagging is not possible or practical. Ensures that the tag contains:

A. The name of the tagger

B. Date

C. Item identified

D. Serial number

E. A brief description of the nonconformance

F. The status of the item (i.e., out-of-service for calibration and/or repair)

2. Determines the disposition of the NCR ensuring that the disposition adequately identifies, describes and resolves the nonconformance. Dispositions such as use-as-is, scrap, repair, rework, return to supplier, or conditional use should be used whenever possible. Technical justification for the acceptability of use-as-is, conditional use, or repair shall be documented. Provides necessary instructions for accomplishing the corrective action including changing existing design documents, test procedures, reports, etc., if applicable. Document changes shall reference the NCR number and be cross-referenced on the NCR report.

3. Determines the root cause and preventive action to prevent recurrence and provides necessary instructions for accomplishing the corrective action.

4. Approves the disposition and obtains the approval of the MIT QA Coordinator.

5. Distributes the NCR to personnel assigned to accomplish the disposition, including the MIT QA Coordinator.

3.6 Assigned Personnel

1. Accomplish the disposition and corrective actions as directed by the NCR.

2. Upon completion of the actions, obtains MIT QA Coordinator's concurrence and/or verification as required on the NCR, signs and returns the NCR to the Graduate Research Assistant.

3.7 Graduate Research Assistant

1. Distributes copies of the complete NCR to the originator and the MIT Principle Investigator and forwards the original NCR to the MIT QA Coordinator for retention.

3.8 MIT QA Coordinator

1. Removes NCR Hold Tag.
2. Ensures that the NCR is retained as a QA record in accordance with AP 3.4, Records Management.

4.0 DEFINITIONS

4.1 Item: an all-inclusive term used in place of any of the following: appurtenance, assembly, component, equipment, material, module, part, structure, subassembly, subsystem, system, or unit.

4.2 Nonconformance: a deficiency in characteristic, documentation, or procedure that renders the quality of an item unacceptable or indeterminate.

5.0 REFERENCES

The following documents were used to compile this AP:

5.1 SNL CSDP PD 5.8, Control of Nonconforming Items

5.2 MIT NED QAPP

5.3 MIT NED AP 3.4, Records Management

6.0 RECORDS

6.1 The NCR and associated documents are QA records and shall be maintained in accordance with AP 3.4, Records Management.

7.0 APPENDICES

7.1 Appendix A, MIT NED Nonconformance Report

7.2 Appendix B, MIT NED Nonconformance Hold Tag

APPENDIX A

MIT NED NONCONFORMANCE REPORT

NCR No: ______________ Date: ___/___/___ Page ____ of ____

Item Identification: ____________________________ Location: ______________

Description of Nonconformance and Requirements:

Originated by: ____________________________________ Date: ___/___/___

Disposition, Justification, Cause, and Preventive Action:

[ ] Void (Explain) [ ] Rework [ ] Repair [ ] Use-As-Is [ ] Scrap

[ ] Return to Supplier [ ] Conditional Use

Implementing Instructions/Procedures/Criteria:

Affected Documents: ____

Probable Cause and Actions Taken to Prevent Recurrence:

Approval/Date:

______________________	______________________
Graduate Research Assistant	MIT QA Coordinator

Verification of Disposition and NCR Closure Approval:

[ ] Acceptable [ ] Unacceptable* [ ] Other Action Required* *(Explain)

Approval/Date:

______________________	______________________
Graduate Research Assistant	MIT QA Coordinator

APPENDIX B

MIT NED NONCONFORMANCE HOLD TAG

Nonconformance Report No. ________

NONCONFORMANCE HOLD

Tagged by: ______________________________

Date: ___/___/___

Item: ____________________ Serial No. ______

Status: ______________________________

To be removed only by MIT QA Coordinator

Front

NONCONFORMANCE HOLD

Description ______________________________

of ______________________________

Nonconformance ______________________________

To be removed only by MIT QA Coordinator

Back

APPENDIX B

PERTINENT MIT QUALITY DOCUMENTS

This appendix contains the following pertinent MIT Quality Documents that are referenced in this thesis:

LIST OF APPROVED VENDORS (page 1 of 4)

Name/Address	Equipment Supplied
AIRCO - New England Lawsbrook Road Acton, MA 01720 (800) 832-6202 Contact: Bill Emmit	Containment Vessel Fill Gases (N_2, He, Ar)
Atlantic Thermal Sales 1-B Business Way P.O. Box 39 Hopedale, MA 01747 (508) 634-9600 Contact: Art Bower	ECS Supplier; Fiberglass Sleeving
Electronic Control System, Inc. Rt. 19 South P.O. Box 2650 Fairmont, WV 26554 (800) 233-0726 Contact: Bill Gray	Heater Rod Control/Alarm Unit; Watts Transducer; Current Transformer
E.I.L. Instruments 21 A Street Burlington, MA 01803 (617) 272-9450	Shunt; Simpson Supplier (digital millivolt meter & analog voltmeter)
General Electric Computer Svs. 215 Salem Street Woburn, MA 01801 (617) 938-1920 Contact: Russ Guglielmo, Linda Vincent Robert Sellon	Calibration Service to NIST standards

LIST OF APPROVED VENDORS (page 2 of 4)

Name/Address	Equipment Supplied
Hewlett Packard, Co. 29 Burlington Mall Road Burlington, MA 01803 (617) 270-7000	Multimeter; Data Acquisition Equipment
Kaufman Company, Inc. 110 Second Street Cambridge, MA 02141 (617) 491-5500	Level, Tools
Massachusetts Engineering Co. 40 Murphy Drive Avon Industrial Park Avon, MA 02322 (508) 580-0550 Contact: Bill Stafford	ASME Pressure Vessel
McMaster-Carr Supply Co. P.O. Box 440 New Brunswick, NJ 08903 (201) 329-3200	Electrical Wire; Valves; Barrier Strips; Compound Pressure Gauge
MIT Laboratory/Physics/Solvents Supply 77 Massachusetts Avenue Cambridge, MA 02139	Electrical Wire; Fuses; DEVCON Epoxy; AIRCO Supplier; Krylon Paint; Vacuum Pump Oil
Newark Electronics 200 West Cummings Park Woburn, MA 01801 (617) 932-9040	Simpson Supplier (analog wattmeter & ammeters); Digital voltmeter

Name/Address	Equipment Supplied
OEM Supply, Incorporated Rt. 136 James Reynolds Road Swansea, MA 02777 (800) 451-7141 Contact: Russell S. Wynne	Watlow Supplier; RTV106 Silicone Sealant
Omega Engineering, Inc. P.O. Box 2284 Stamford, CT 06906 (800) 826-6342	Thermocouple Wire and Multipair Cable; Relays; Controllers; Ribbon Heater; Omegabond Epoxy; Barrier Strips
Piping Specialties, Inc. 56 Pickering Street P.O. Box 315 Needham, MA 02192 (617) 444-9092 Contact: Lock Spain	Pressure Safety Relief Valves (Anderson, Greenwood & Co. Supplier)
Sheffield Progressive, Inc. 195 North Street P.O. Box 187 North Reading, MA 01864 (617) 944-7886 Contact: Matthew Dietel	Rod Support Plafes; Boundary Condition Box Support Structure
Thermo Electric Co., Inc. Saddle Brook, NJ 07662 (201) 843-5800	Compression Fittings

LIST OF APPROVED VENDORS (page 4 of 4)

Name/Address	Equipment Supplied
Watlow 12001 Lackland Road St. Louis, MO 63146 (314) 878-4600	Heater Rods; Strip Heaters; Flexible Heaters

MEMORANDUM

OF

UNDERSTANDING

RE: Project Tasks Quality Level

The MIT Nuclear Engineering Department (NED) Quality Assurance Program Plan (QAPP) and Administrative Procedures (APs) require that a "Quality Level Assignment Checklist," AP 5.6 Appendix C, be completed for each task to determine the appropriate Quality Level. A Checklist (attached) has been completed for the project, as a whole, to determine the most stringent Quality Level that could ever be assigned to any project task. **The assigned project Quality Level is QL2. This level will be assigned to all project tasks. QL2 requires full compliance with the MIT NED QAPP and APs.** This level does not have to be recorded on any documentation (however, it is highly recommended). If there is no recorded Quality Level, it should be understood that the Quality Level is QL2.

Phyllis M. Lovett ____________ 04-01-91
Graduate Research Assistant — Date

Phyllis M. Lovett ____________ 04-01-91
Approved MIT QA Coordinator — Date

Neil E. Todreas ____________ 4/2/91
Approved MIT Principle Investigator — Date

APPENDIX C (page 1 of 4)

QUALITY LEVEL ASSIGNMENT CHECKLIST

Project Contract No. 42-5638 Contract Organization Sandia National Laboratories

MIT NED Participants Prof. Neil E. Todreas (MIT Principle Investigator), R. Manteufel, P. Lovett (Graduate Research Assistants)

Project Title Internal Heat Transfer Modeling Methods Development Program.

Q-Level Assignment Criteria: The definitions of quality level are given in AP 5.6, Quality Program Levels of Effort.

For convenience, the Quality Level definitions are:

Quality Level 1 (QL1): Items or activities assigned this classification are ones where an omission, error, or failure could directly impact public radiological health and safety. From a mechanistic perspective, if an adverse radiological effect (exceeding regulatory limits) may be initiated by an omission, error, or failure of an item or activity, then that item or activity must be classified as QL1. The determination of which initiating events involving items and activities that might result in the above effects must be made on a case-by-case basis at the time of classification. Criticality events and failure of containment and shielding are among the events that require analysis. QL1 items and activities shall meet the basic and supplemental requirements of ANSI/ASME NQA-1.

Quality Level 2 (QL2): Items and activities assigned this classification are ones, under the direct control of the OCRWM CSDP, where an omission, error, or failure could lead to circumstances that could require QL1 items or activities to perform their safety-related function. Therefore, an indirect relationship exists between QL2 items and activities and adverse radiological effects to public health and safety. An example might be the brakes on a trailer carrying a nuclear spent fuel cask. A failure of the brakes might precipitate an accident which in turn could challenge the cask containment. QL2 items and activities shall meet the basic and selected supplemental requirements of ANSI/ASME NQA-1.

Quality Level 3 (QL3): QL3 is for assignment to OCRWM activities selectively chosen because of special programmatic importance other than radiological safety. These include mission-oriented activities controlled by DOE orders and procedures which reflect good technical management practices for the assurance of quality. Additionally, NQA-1 requirements may be selectively applied as determined by line management.

APPENDIX C (page 2 of 4)

QUALITY LEVEL ASSIGNMENT CHECKLIST

The key to defining appropriate quality levels for each task is to use a logic network to identify how a "failure" in the task (or subtask) or erroneous results can impact one of the cask safety functions; criticality control, shielding, containment, or heat removal. An activity that can have a "direct" (QL1) impact on a cask safety function is essentially a dominant, single failure mode; i.e., if an error or failure occurs, a cask safety function is directly compromised. In a "fault tree" or "event tree," a set of "directly" affecting events will intersect through an "or" gate; i.e., each event can alone have a major impact on safety.

On the other hand a set of "indirect" events or activities requiring QL2 quality control will intersect through an "and" gate in a failure mode logic network. That is, an error or failure occurs in one or more other independent tasks or activities.

Finally, QL3 requirements are specified for all other activities. For other programs, the definition above requires QL3 quality control for all activities which have some impact to health and safety.

The appropriate quality level of a task can be determined by addressing questions related to the task's impact on health and safety, program direction, budget or schedule, or the functional design basis and subsequent performance of criticality, shielding, containment, or thermal safety features of a cask. The questions may be applied to any task category such as experimental, computational, safety assessments, software development, testing, data acquisition, reporting, etc. All questions will not necessarily apply to every task. An affirmative reply in the highest quality category determines the QA requirements for the task.

<u>Q-Level 1</u>:

		Yes	No
1.	Is the task on the SNL CSDP Q-list?	___	X
2.	Has DOE specified QL-1 QA requirements in program documents for this task?	___	X
3.	Could erroneous task results directly and independently result in exposure to radiation or release of radioactive materials (RAM) in excess of the limits specified in 10CFR71 during normal or accident conditions or transport?	___	X
4.	Do the results of this task directly determine the design criterion or functional design basis of a Q-list item? (Such as criticality, shielding, containment or heat management effectiveness?)	___	X
5.	Are QL1 QA requirements appropriate for this task for other reasons?	___	X

APPENDIX C (page 3 of 4)

QUALITY LEVEL ASSIGNMENT CHECKLIST

Q-Level 2:

		Yes	No
1.	Could failure or malfunction of an item or activity associated with this task have a potentially significant impact on worker or public radiological or nonradiological health and safety?	X	
2.	Would loss of task data or records result in significant program costs or schedule delays?		X
3.	Will the task results support critical (SNL/DOE) program decisions such as which cask designs will be developed, fabricated, or procured for fleet use?	X	
4.	Could erroneous task results, in combination with abnormal factors, result in reduced reliability of the criticality, shielding, containment, or heat removal capabilities of a cask?	X	
5.	Does this task support the development of a design "standard" for a cask safety feature?	X	
6.	Are QL2 QA requirements for this task appropriate for other reasons?	X	

Q-Level 3:

		Yes	No
1.	Does the task support the DOE CSDP program?	X	
2.	Does the task have a potential impact on public health and safety?	X	
3.	Will the task involve validation of theoretical or analytical models relating to cask design?	X	
4.	Does the task involve feasibility assessments of advanced technological applications with the results intended to impact CSDP program direction?	X	
5.	Does the task involve parametric or sensitivity analyses that will be used to focus more detailed and expensive efforts in the future?	X	

MIT NED Administrative Procedure	Title: Quality Program Levels of Efforts	No. 5.6 Page 9 of 9 Date: 03/27/91 Revision: A

APPENDIX C (page 4 of 4)

QUALITY LEVEL ASSIGNMENT CHECKLIST

		Yes	No
6.	Would loss of task data and records or loss of task "memory" in the event of personnel changeover jeopardize the ability to meet outstanding program milestones?	X	___
7.	Are QL3 task requirements appropriate for other reasons?	X	___

ASSIGNED TASK QUALITY LEVEL: QL2

Graduate Research Assistant — Date: 03-29-91

Approved MIT QA Coordinator — Date: 03-29-91

Approved MIT Principle Investigator — Date: 3/29/91

DEPARTMENT OF NUCLEAR ENGINEERING
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
77 Massachusetts Avenue Cambridge, Massachusetts 02139

Room 24-219

5296

January 25, 1991

Mr. Richard M. Baehr
Quality Assurance Coordinator
Department 6320
Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 87185

Dear Mr. Baehr,

In response to your letter dated December 17, 1990, this letter will clarify the concern you had with the MIT Nuclear Engineering Department Quality Assurance Program Plan (QAPP). Your concern was with the responsibility clarity in a statement on page 6 in paragraph 2.3, line 1, "The QA Coordinator is responsible ....". The QA Coordinator at MIT is responsible for this action. A change will be made to the MIT QAPP to clarify the actual responsibility, and an updated MIT QAPP will be sent to you.

As stated in your December 17, 1990 letter, with the clarification of this statement, our MIT QAPP is acceptable to support SNL activities conducted for Contract 42-5638.

Sincerely,

Neil E. Todreas
Professor
Nuclear Engineering

cc: N. Brown, SNL Division 6322
G. Hohnstreiter, SNL Division 6322

Sandia National Laboratories

Albuquerque, New Mexico 87185

December 17, 1990

Dr. Neil E. Todreas
Professor, Nuclear Engineering
Department of Nuclear Engineering
Massachusetts Institute of Technology
77 Massachusetts Avenue
Cambridge, Massachusetts 02139

Dear Dr. Todreas:

I have reviewed the Quality Assurance Program Plan, MIT NED QAPP, Rev. A, 10/12/90, that was developed by MIT for Sandia National Laboratory Contract 42-5638 and have one concern. Page 6, paragraph 2.3, line 1, states "The QA Coordinator is responsible.......". It is not clear whether the QA Coordinator mentioned is the MIT or SNL QA Coordinator.

With the clarification of this statement, your QAPP will be acceptable. The plan appears to be comprehensive and adequate for support of SNL activities conducted for Contract 42-5638.

Sincerely,

Richard M. Baehr

Richard M. Baehr, QA Coordinator
Transportation Systems Development
Department 6320

RMB:6320

copy to:
6323 T. L. Sanders
6320 N. N. Brown
6320 R. M. Baehr
6323 CSDP File 15.40
6323 CSDP QA File 15.40

Sandia National Laboratories, Albuquerque
Transportation System Development Department 6320

QUALITY ASSURANCE AUDIT REPORT

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Cambridge, Massachusetts

Audit No. MIT-A91-1
Conducted April 4, 1991

Richard M. Baer 4/9/91
Lead Auditor Date

CSDP QA File 15.16 (MIT-A91-1)

TABLE OF CONTENTS

1.0 INTRODUCTION

A Quality Assurance (QA) programmatic compliance audit was conducted on April 4, 1991, by Richard M. Baehr, Sandia National Laboratories (SNL), Transportation System Development Department (TSDD), at Massachusetts Institute of Technology (MIT), Nuclear Engineering Department (NED), Cambridge, Massachusetts. The NED is performing conductive and radiative heat transfer studies in enclosed spent fuel rod bundles in spent fuel cask baskets under SNL Contract 42-5638. In particular, MIT was tasked to:

- Conduct a literature study on the experimental and numerical analysis of the heat transfer processes in horizontal rod bundles in spent fuel cask baskets.
- Develop test hardware and conduct experimental studies of the natural convection and radiation heat transfer processes in the interior of rod bundle assemblies in the horizontal orientation.
- Perform parametric studies and deduce the basic scales of heat transfer processes.
- Develop predictive tools that can be used to determine the three modes of heat transfer and the maximum fuel pin temperature in horizontal fuel bundles. Benchmark these results using experimental data and results available in the literature.

2.0 AUDIT SCOPE

The scope of this audit was to determine the degree of compliance of the MIT QA Program and implementing procedures with the QA requirements in the Statement of Work for SNL Contract 42-5638.

Objective evidence was examined to the depth necessary to determine the applicability, effectiveness, and degree of compliance of the MIT QA Program to the above mentioned requirements. Appendix A lists pertinent documents reviewed.

3.0 AUDIT TEAM AND PERSONNEL CONTACTED

The QA Audit Team consisted of Richard M. Baehr, SNL Lead Auditor. Dr. N. Todreas, Phyllis M. Lovett, and Randall D. Manteufel were contacted during the audit. (See Appendix B).

4.0 PERFORMANCE AND RESULTS OF THE AUDIT

An entrance meeting was held on the morning of April 4, 1991, with Dr. N. Todreas et al., to review a. the audit plan, b. audit scope and duration; c. agenda for the audit; to establish channels of communication; and to set the time for the close-out meeting.

Dr. Todreas briefed the audit personnel on the project progress and on the ability and capability of MIT to meet the QA requirements set forth in SNL Contract 42-5638.

A close-out meeting was held with MIT personnel the evening of April 4, 1991, to present the audit results and clarify any misunderstandings.

The Lead Auditor received excellent cooperation throughout the audit. MIT has an effective QA program in place which satisfies the QA requirements of SNL Contract 42-5638.

5.0 SUMMARY OF RESULTS AND EFFECTIVENESS OF PROGRAM ELEMENTS AUDITED

The literature study on experimental and numerical analysis of heat transfer processes in horizontal rod bundles in spent fuel baskets has been completed.

Test hardware has been constructed and data will be taken in the near future.

Parametric studies to deduce basic scales of heat transfer processes have been started.

The development of predictive tools to determine modes of heat transfer in horizontal fuel bundles has been started and work is in progress.

Required deliverables have been/or are being submitted to SNL at the required time.

The MIT NED has an effective QA program in effect which satisfies the QA requirements of SNL Contract 42-5638.

APPENDIX A

DOCUMENTS REVIEWED DURING AUDIT

DOCUMENTS:

1. SNL Contract 42-5638, Internal Heat Transfer Modeling Methods Development Program.

2. MIT NED Quality Assurance Manual.

APPENDIX B

MASSACHUSETTS INSTITUTE OF TECHNOLOGY PERSONNEL CONTACTED DURING AUDIT

MIT-A91-1
April 4, 1991

Name	Entrance Meeting	Audit	Exit Meeting
Dr. N. Todreas	X		X
Phyllis M. Lovett	X	X	X
Randall D. Manteufel	X	X	

Sandia National Laboratories

Albuquerque, New Mexico 87185

April 9, 1991

Ms. Phyllis M. Lovett
Massachusetts Institute of Technology
Department of Nuclear Engineering
138 Albany Street, Room NW12-219
Cambridge, Massachusetts 02139

Dear Phyllis:

Subject: Close-out of Audit MIT-A91-1

Attached you will find a copy of the audit report for the Quality Assurance Program audit that was conducted at the Massachusetts Institute of Technology, Nuclear Engineering Department, April 4, 1991, by Richard M. Baehr.

There there were no reported Audit Findings or Observations and Audit MIT-A91-1 is closed out.

Sincerely,

Richard M. Baehr

Richard M. Baehr, QA Coordinator
Transportation Systems Development
Department 6320

RMB:6320
Attachment

Copy to: w/attach.
6320 R. E. Luna, Actg. (w/o attach.)
6322 G. F. Hohnstreiter
6323 T. L. Sanders
6323 N. N. Brown
6320 R. M. Baehr
6323 CSDP QA File 15.16 (MIT-A91-1)

GE Electronic Services

General Electric Company
215 Salem Street
Woburn, MA 01801
(617) 938 1920

March 1, 1991

Ms. Phyllis Lovett, NW 12-219
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
138 Albany Street
Cambridge, MA 02139

Dear Phyllis:

Per our phone conversation on February 28, 1991, the two (2) Hewlett Packard boards, HP44708A and HP44713A, do not require calibration. After our last conversation, I called Hewlett Packard to verify this information. These boards are "relays" only, and have no effect on the system's accuracy; therefore, do not require calibration. If you have a problem with operation, or suspect an operation problem, please call.

Thanks again for your continued support. Do not hesitate to call with any questions regarding support services; we welcome the opportunity to help.

Sincerely,

Robert S. Sellon
Major Accounts Manager
(617) 328-4725

RSS/ps

APPENDIX C

CRITERIA FOR SELECTING HEATER ROD LENGTH AND THICKNESS

This appendix contains the analysis performed by R.D. Manteufel to provide justification of the selection of a length of 24.5 inches and a thickness of 0.049 inch for the Heater Rods used in the experiment. The decision to purchase Heater Rods 24.5 inches in length and 0.049 inch in thickness was made by R.D. Manteufel with the approval of N.E. Todreas in June 1990.

Criteria for Selecting Rods of Length 24"

We present an argument for determining an appropriate length of a heated rod. Qualitatively, the length of the rod should be long enough so that thermal "end effects" do not overwhelm the temperature readings which will be taken in the middle of the heater rods. Infinitely long rods have the theoretical advantage of having no end effects, yet infinite rods are an impossibility. The following calculations are used selected an appropriate heater rod length.

We assume that the rods have the following physical characteristics: outside diameter of 3/8" and copper wall thickness of 0.049". The rod diameter of 3/8" was chosen to be close to the nominal PWR fuel rod size. Copper was chosen as the sheathing material because its high conductivity will eliminate circumferential temperature gradients. A schematic of the heater rod is given in Figure C-1.

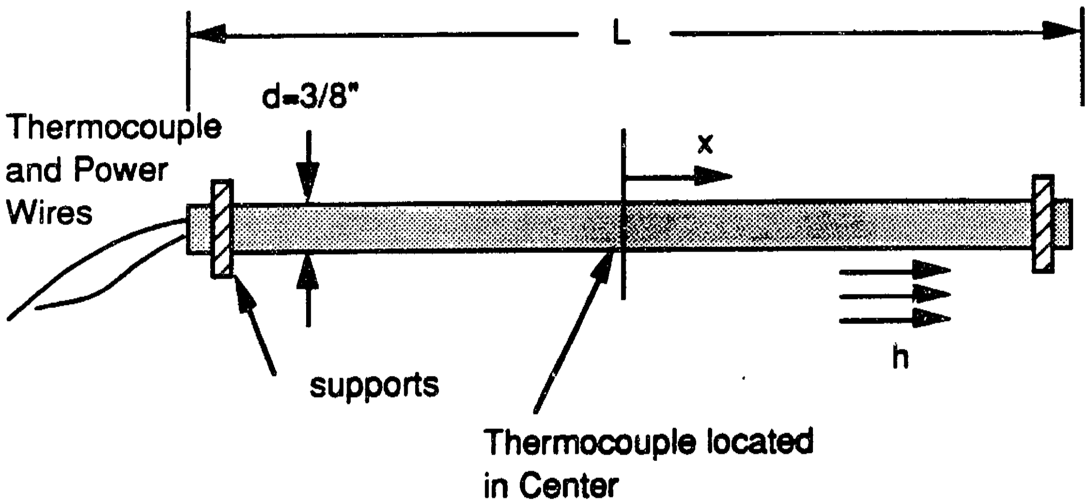


Figure C-1: Schematic of Heater Rod

A basic assumption is the rods have the thermal behavior of a "heat generating fin". The governing equation for the fin is simply stated:

$$\frac{d^2\Theta}{dx^2} - \frac{h\,P}{k\,S}\Theta + \frac{q'}{k\,S} = 0 \qquad (1)$$

where:

h	average convective heat transfer coefficient
k	tube material conductivity (copper, 401 W/m-K)
S	tube cross-sectional area ($S = \pi\, d\, \Delta t$)
P	tube cross-sectional perimeter ($P = \pi\, d$)
q '	axial heat generation rate
Θ	temperature potential
d	tube diameter
Δt	tube wall thickness

The governing boundary conditions are:

BC#1 insulated end, i.e., symmetry

$$\frac{d\Theta}{dx}(x=0) = 0 \tag{2}$$

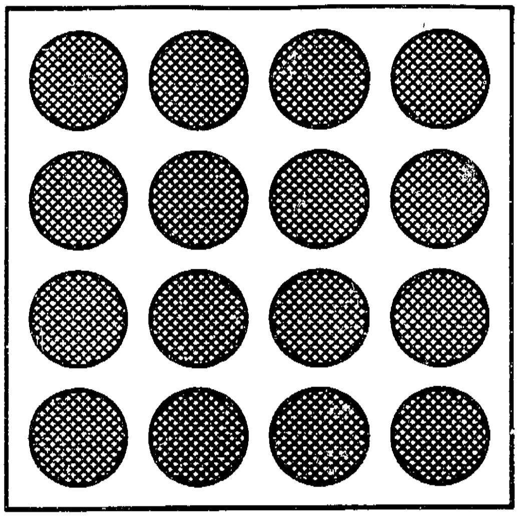
BC #2, convective end used to account for the increased heat transfer mechanism available in the rod support plate.

$$-k\, S\, \frac{d\Theta}{dx}(x=L/2) = \Theta(x=L/2)\, h\, P\, \Delta x_{eq} \tag{3}$$

where

Δx_{eq} equivalent additional length for the support plate end boundary condition

The second boundary condition is a statement of the conservation of energy at the supported end. It is derived by viewing the supports as offering a lumped conduction path. The term "Δx_{eq}" is derived by considering the radial conduction path is through the support plates. In comparison, Equation (1) considered the axial temperature profile for a single rod. To assist the reader in making this mental switch, from axial to radial, we include a diagram which shows a cross-section of a 4x4 rod bundle:



From previous work, we have derived an equivalent thermal conductivity for the stagnant gas conduction and radiative heat transfer mechanisms in the radial direction of a horizontal spent fuel assembly. Similarly, we can derive an equivalent conductivity for the support plate. For a typical PWR with p/d=1.3, we found the equivalent conductivity is a factor 2.6 greater that the fill gas conductivity. Having an estimate of the k_{eq}, one can estimate the maximum temperature in a square homogeneous region assuming isothermal boundaries and uniform heat generation:

$$T_{max} - T_{surf} = 0.074\, q' / k_{eq}$$

or

$$T_{max} - T_{surf} = 0.074\, q / \Delta x\, k_{eq} \qquad (3.5)$$

where q' is the heat generation per unit depth, q is total heat generation, and Δx is depth.

We assume the thermal behavior in the support plate is similar to the thermal behavior in the fill gas, hence Equation (3.5) would be valid for both. From Equation (3.5), we can identify a conductance: $G = \Delta x\, k_{eq}$. This conductance is similar to the traditional conductance: $G = k\, A/L$. The only difference is that the geometrical information of interest for this problem is Δx, the depth.

For computational purposes, we assume that the end support acts as an additional area for convective heat transport. The basic assumption is equal conductance:

$$G_{support} = G_{eq}$$

or

$$k_{ss}\, \Delta x_{ss} = k_{eq}\, \Delta x_{eq}$$

where

k_{ss}	stainless-steel conductivity (15 W/m-K)
k_{eq}	equivalent thermal conductivity of the rod bundle
Δx_{ss}	stainless-steel support plate thickness (0.015")
Δx_{eq}	previously defined equivalent additional length

We solve for Δx_{eq}

$$\Delta x_{eq} = (k_{ss} / k_{eq})\, \Delta x_{ss}$$

which corresponds to the area (length) on the right hand side of equation (3).

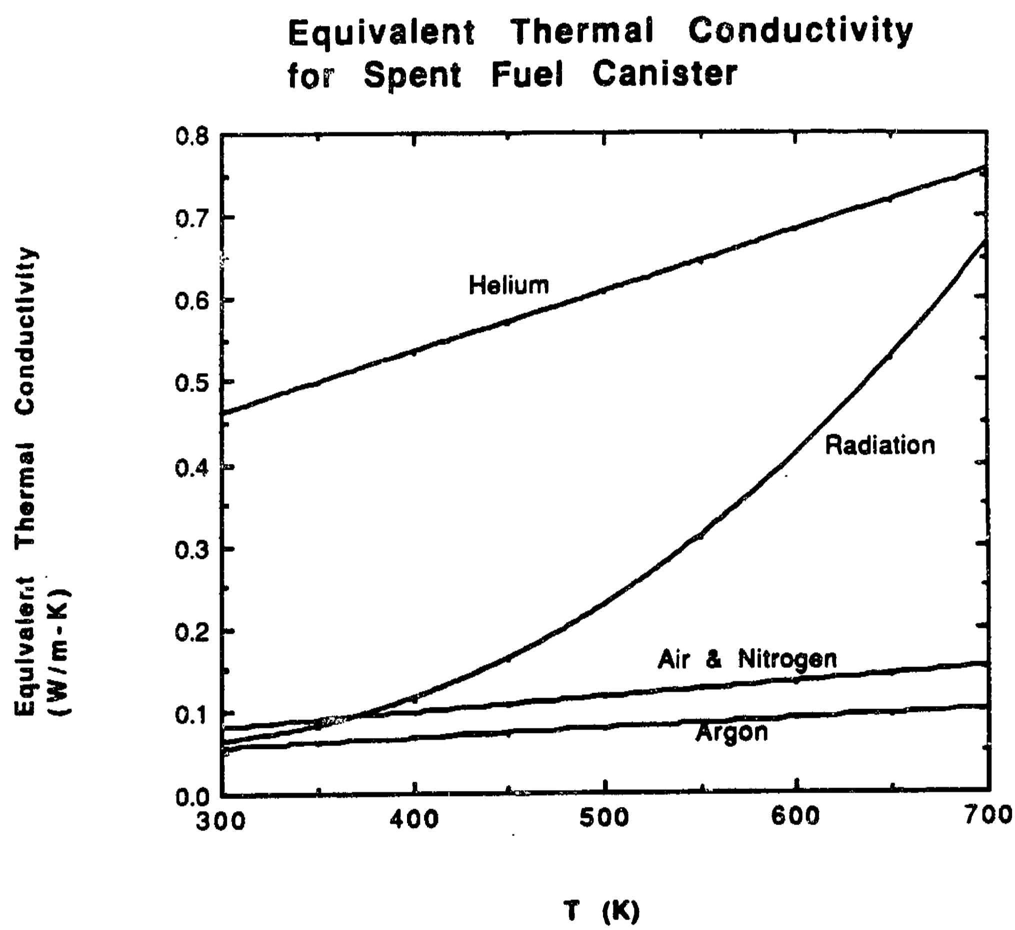


Figure C-2: Equivalent Thermal Conductivity for Radiative Heat Transfer and Stagnant Gas Conduction Heat Transfer

From Figure C-2 (reproduced from R. Manteufel's presentation given at the SNL-DOE sponsored Cask Cavity Heat Transfer Workshop, January 9, 1990 in Alb. NM), one can estimate the equivalent thermal conductivity to be at least 0.1 W/m-K in a spent fuel assembly.

We can estimate the average heat transfer coefficient, h, to be ~5 W/m^2-K in two ways:

(1) lookup the typical lower limit described in heat transfer textbooks, or
(2) compute the equivalent radiative heat transfer coefficient, $h_{rad} = 4 \sigma T^3$

Heat transfer textbooks suggest a convective heat transfer coefficient for natural convection in air to be about 5-25 W/m^2-K, hence 5 W/m^2-K is a conservative assumption. The equivalent radiative heat transfer coefficient is calculated for the lower limit of the temperature range of interest (50 - 100 C) and is tabulated in Table C-1. From the data in Table C-1, the assumed valued of 5 W/m^2-K can be considered a conservative. It will be shown that a larger h will minimize the support plate influence on the centerline temperature measurements.

Table C-1: Equivalent Radiative Heat Transfer Coefficient

T (C)	h_{rad} (W/m^2-K)
50	7.7
75	9.6
100	11.8

We proceed to solve the mathematical problem of a second order ODE with two distinct boundary conditions. The general solution for the ODE (Equation 1) is:

$$\Theta(x) = C_1 \sinh(B\,x) + C_2 \cosh(B\,x) + \frac{q'}{h\,P} \qquad (4)$$

where we introduce a new parameter

$$B^2 = (h\,P)/(k\,S)$$

and C_1, C_2 are constants to be determined from the boundary conditions.

When BC#1 (Equation 2) is applied, we find that $C_1 = 0$. When BC #2 (Equation 3) is applied, we find:

$$-k\,S\,C_2\,B \sinh(B\,L/2) = \left[C_2 \cosh(B\,L/2) + \frac{q'}{h\,P}\right] h\,P\,\Delta x_{eq}$$

Solving for C_2 we find:

$$C_2 = \frac{-q'\,\Delta x_{eq}}{k\,S\,B\,\sinh(B\,L/2) + h\,P\,\Delta x_{eq}\cosh(B\,L/2)} \qquad (5)$$

Substituting into our general solution we find:

$$\Theta(x) = \frac{-\,q'\,\Delta x_{eq}}{k\,S\,B\,\sinh(B\,L/2) + h\,P\,\Delta x_{eq}\cosh(B\,L/2)}\cosh(B\,x) + \frac{q'}{h\,P}$$

If we had an infinite rod, the temperature would not be influenced by the end conditions and would be equal to:

$$\Theta_{max} = \frac{q'}{h\,P}$$

Therefore, we introduce a new temperature potential, which is normalized by the infinite rod temperature potential:

$$\Theta^*(x) = \frac{\Theta(x)}{\Theta_{max}}$$

The general solution is then given by:

$$\Theta^*(x) = 1 - \frac{B\,\Delta x_{eq}}{\sinh(B\,L/2) + B\,\Delta x_{eq}\cosh(B\,L/2)}\cosh(B\,x)$$

For comparison purposes, we compute the above normalized centerline temperature, $\Theta_o^* \equiv \Theta^*(0)$, for different total rod lengths (L).

$$\Theta_o^*(L, B, \Delta x_{eq}) = 1 - \frac{B\,\Delta x_{eq}}{\sinh(B\,L/2) + B\,\Delta x_{eq}\cosh(B\,L/2)}$$

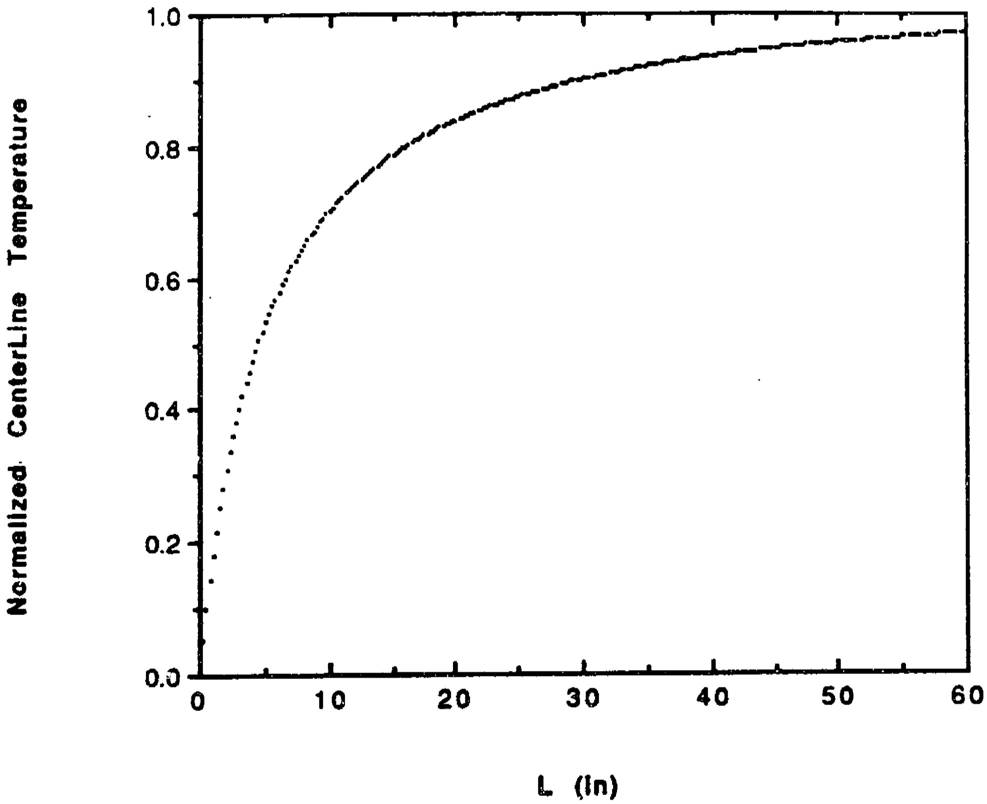


Figure C-3: Normalized Centerline Temperature as a Function of Rod Length

In Figure C-3, it is clear that the rod length does influence the centerline rod temperature (as one would expect). The influence is greatest for short rods. The influence diminishes as the rod length increases. The reader is reminded of two important aspects:

(1) In an actual experiment, the rods must be supported and the supports can't be arbitrarily far apart. In previous experiments, the supports could not be located greater than ~ 2' apart.

(2) We have made conservative assumption for this calculation.

The statement of conservative assumptions can be seen by the influence of B and Δx_{eq} on the solution. For comparison purposes, in Figure C-4, we have plotted the normalized centerline temperature for different values of B which vary by a factor of 2, keeping Δx_{eq} constant. Similarly, in Figure C-5, we vary Δx_{eq} by a factor of 2.

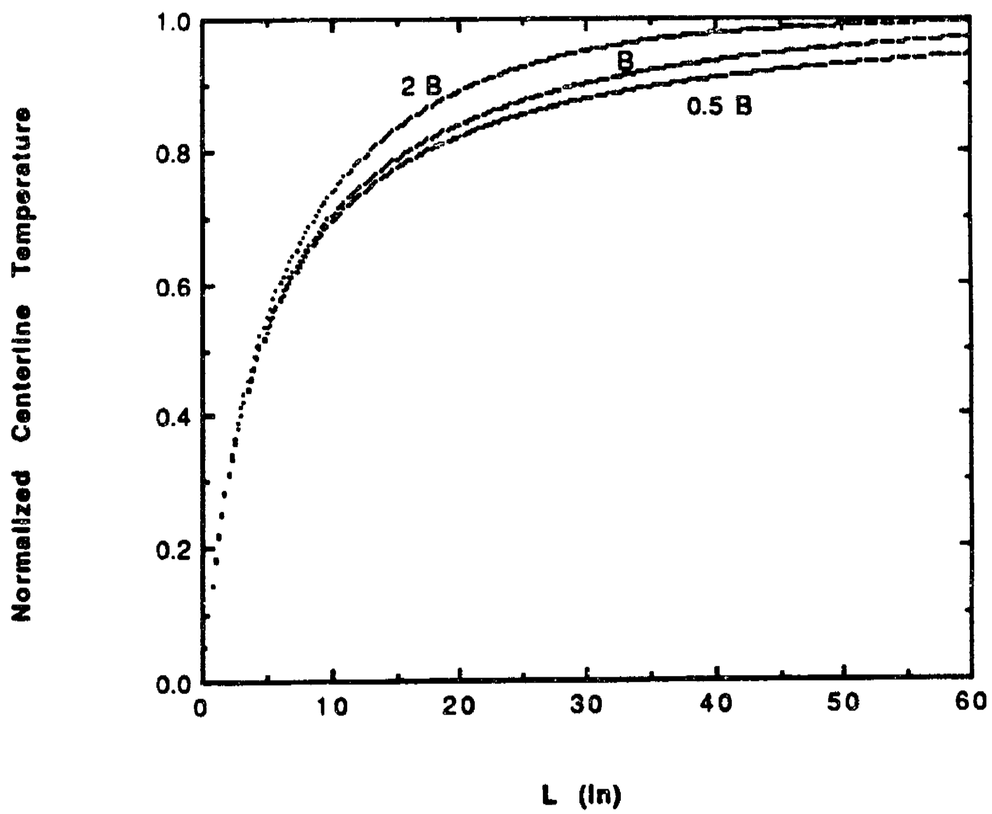


Figure C-4: Effect of the Parameter B on Normalized Centerline Temperature

From Figure C-4, we see that as B decreases, the centerline temperature is more strongly influenced by the support plate. Recalling the definition of B, B= (h P) / (k S), we note that a larger value of h will increase B. Recalling our assumption of a low value of h = 5 W/m^2-K, we now recognize this to be a conservative approximation (as we originally expected).

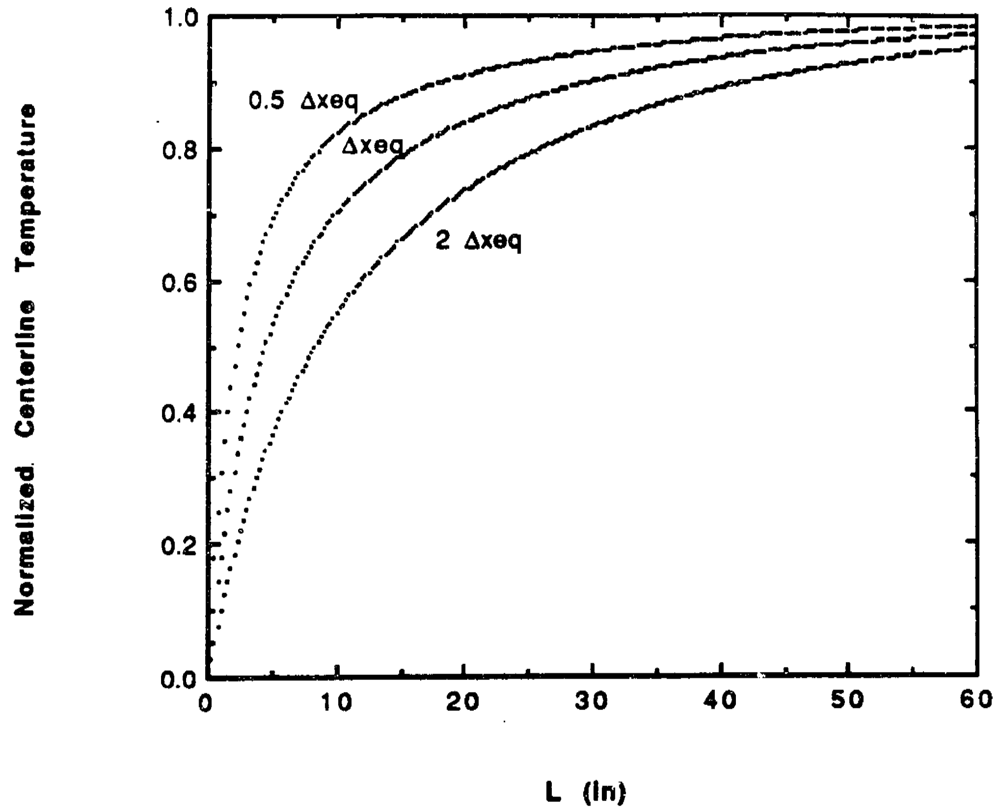


Figure C-5: Effect of the Parameter Δx_{eq} on Normalized Centerline Temperature

The equivalent fill gas conductivity was assumed to be 0.1 W/m-K from Figure C-2. From the definition of Δx_{eq}: $\Delta x_{eq} = (k_{ss} / k_{eq}) \Delta x_{ss}$, we note that a smaller value of k_{eq} will increase Δx_{eq}. A smaller assumed conductivity will increase the influence of the support plates on the centerline temperature. Hence, the assumption of a low thermal conductivity is a conservative assumption.

From Figure C-3, we note that a rod of length ~24" will allow minimal support influence on the centerline temperature measurements. For this reason, 24" was selected to be the rod length.

The general solution for the above problem has been solved using Mathematica and the applicable code is presented in Table C-2.

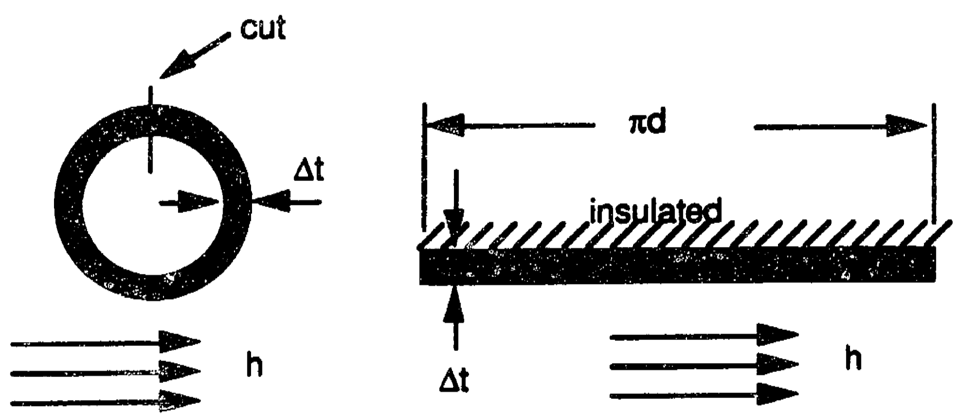
Table C-2: The Code used to Compute the Centerline Temperature as a Function of the Rod Length

```
(* code used to compute rod centerline temperature
as a function of rod length *)

in            = 0.0254
dia           = 3/8 in
kcopper       = 401.0
wallthickness = 0.049 in
sectionalarea = N[Pi] dia wallthickness
perimeter     = N[Pi] dia
B = ( (hconv perimeter) / ( kcopper sectionalarea) )^0.5
ssthickness   = 0.015 in
kss           = 15
krad          = 0.1
addlength     = ( kss / krad ) ssthickness

(* len input in inches, len in total length of rod *)

Tcenter[ len_, bigB_, Δxeq_ ] := ( 1 - bigB Δxeq /
 (Sinh[bigB len / 2 in] + bigB Δxeq Cosh[bigB len / 2 in]))
```

Criteria for Selecting Rod Sheathing

We present a quantitative analysis for the determination of an appropriate rod sheathing material. In previous experiments, the rod walls offered significant circumferential conductive resistance compared to the average surface resistance (due to radiative and/or convective heat transfer). These two resistances can be compared in the non-dimensional ratio called the Biot number. In Cox's Ph.D. Thesis, he recommended that future experiments consider heater rods made with copper sheathing. We will compare a typical Biot number for Cox's rods with our new rods.

The following diagram is introduced to assist in the discussion:



For analysis purposes, we will compare the 360 degree circumferential conductive resistance with the average convective resistance. The conductive resistance is approximately $R_{cond} = (\pi\ d) / (k\ \Delta t)$. The convective resistance is $R_{conv} = 1 / (h\ \pi\ d)$. The average convective heat transfer coefficient will be computed considering only radiative heat transfer at a 350 C, a high estimate: $h_{rad} = 4\ \sigma\ T^3 = 55\ W/m^2\text{-}K$. We compute the Biot number:

$$Bi = R_{cond} / R_{conv} = h\ (\pi\ d)^2 / (k\ \Delta t)$$

When Bi << 1, one would not expect circumferential temperature gradients. When Bi >> 1, one can expect severe circumferential temperature gradients. From Cox's rod data, we can compute an approximate Biot number:

$d = 0.25"$

$k = 15$ W/m-K (stainless-steel)

$\Delta t = 0.035"$

hence

$$Bi = 1.6$$

We can compute a Biot number for the new rods:

$d = 3/8"$

$k = 400$ W/m-K (copper)

$\Delta t = 0.049"$

hence

$$Bi = 0.0987$$

For comparison purposes, the Bi number for our new rods is 6/100's of Cox's. We expect that our experiment will eliminate circumferential temperature gradients.

APPENDIX D

DATA ACQUISITION PROGRAM

This appendix contains the data acquisition computer program written by S. Friedenthal and the author. The computer program is written in the language Hewlett Packard Basic 5.13.

```
10    ! PROGRAM TO READ THERMOCOUPLE TEMPERATURES AND DISPLAY/PRINT RESULTS
20    DIM Yes_no$[1]
30    LINPUT " DO YOU WANT TO ENTER THE RUN ID NUMBER",In$
40    ENTER In$;Yes_no$
50    Yes_no$=UPC$(Yes_no$)
60    IF Yes_no$="Y" THEN GOSUB 960       ! PROMPT FOR RUN ID NUMBER
70    PRINT "       ****  MEASURING THERMOCOUPLE TEMPERATURES ****"
80    REAL Tmp1(0:99,0:19),Tmp2(0:99,0:19),Tmp3(0:99,0:19),Tmp4(0:99,0:19),Tmp5(
0:99,0:19)
90    REAL Temp1(0:19),Temp2(0:19),Temp3(0:19),Temp4(0:19),Temp5(0:19)
100   INTEGER Index1(0:19),Index2(0:19),Index3(0:19),Index4(0:19),Index5(0:19)
110   OUTPUT 709;"NPLC 5"                    ! AVERAGE OVER 5 POWER LINE CYCLES
120   OUTPUT 709;"RST"
130   OUTPUT 709;"CONFMEAS TEMPK, 100-119, NSCAN 100, USE 700"
140   ENTER 709;Tmp1(*)
150   OUTPUT 709;"RST"
160   OUTPUT 709;"CONFMEAS TEMPK, 200-219,NSCAN 100,USE 700"
170   ENTER 709;Tmp2(*)
180   OUTPUT 709;"RST"
190   OUTPUT 709;"CONFMEAS TEMPK, 300-319,NSCAN 100, USE 700"
200   ENTER 709;Tmp3(*)
210   OUTPUT 709;"RST"
220   OUTPUT 709;"CONFMEAS TEMPK, 400-419,NSCAN 100,USE 700"
230   ENTER 709;Tmp4(*)
231   OUTPUT 709;"RST"
240   OUTPUT 709;"CONFMEAS TEMPK, 500-519,NSCAN 100, USE 700"
250   ENTER 709;Tmp5(*)
260   !
270   FOR I=0 TO 19
280     Total1=0
290     Total2=0
300     Total3=0
310     Total4=0
320     Total5=0
330     FOR J=0 TO 99
340       Total1=Total1+Tmp1(J,I)
350       Total2=Total2+Tmp2(J,I)
360       Total3=Total3+Tmp3(J,I)
370       Total4=Total4+Tmp4(J,I)
380       Total5=Total5+Tmp5(J,I)
390     NEXT J
400     Temp1(I)=Total1/100
410     Temp2(I)=Total2/100
420     Temp3(I)=Total3/100
430     Temp4(I)=Total4/100
440     Temp5(I)=Total5/100
450     Index1(I)=100+I
460     Index2(I)=200+I
470     Index3(I)=300+I
480     Index4(I)=400+I
490     Index5(I)=500+I
500   NEXT I
```

```
510   PRINTER IS CRT                          ! SETS PRINTOUT TO SCREEN
520   GOSUB 630                               ! PRINT RESULTS SUBROUTINE
530   GOSUB 850                               ! GET YES/NO RESPONSE FOR PRINTOUT
540   IF Print$="YES" THEN                    ! IF USER WANTS A PRINTOUT ...
550     GOSUB 5010                            ! PRINT TEMP. DISTRIBUTIONS
560     PRINTER IS PRT                        ! SETS PRINTOUT TO PRINTER
570     GOSUB 630                             ! PRINT RESULTS SUBROUTINE
580   END IF
590   DISP "SAVE DATA TO FILE (Y/N)?";
600   INPUT "",Yes_no$
610   IF Yes_no$="Y" THEN GOSUB 2010           ! SAVE DATA TO FILE
620   GOTO 6550                               ! GOTO END OF PROGRAM FOR "END"
630     ! ********  PRINT SUB-ROUTINE ********
640   PRINT "                    ******* THERMOCOUPLE TEMPERATURES *******"
650   PRINT ""
660   PRINT DATE$(TIMEDATE)
670   PRINT TIME$(TIMEDATE)
680   PRINT ""
690   PRINT "RUN ID. NO. ";Run_id_no$
700   PRINT ""
710   PRINT ""
720   FOR I=0 TO 19
730     PRINT Index1(I);TAB(7);Temp1(I);TAB(20);Index2(I);TAB(25);Temp2(I);TAB(4
0);Index3(I);TAB(45);Temp3(I);TAB(60);Index4(I);TAB(65);Temp4(I)
740     NEXT I
750     PRINT ""
760     PRINT ""
770     FOR I=0 TO 19
780     PRINT Index5(I);TAB(7);Temp5(I)
790     NEXT I
800   PRINTER IS CRT                                    ! RETURN DISPLAY TO SCREEN
810   RETURN
820   ! ***** END OF PRINT SUBROUTINE ******
830   !
840   !
850   ! ********** GET USER RESPONSE SUBROUTINE *********
860   LINPUT "COPY OUTPUT TO PRINTER (Y/N)?",In$
870   ENTER In$;Yes_no$
880   IF Yes_no$="Y" OR Yes_no$="y" THEN
890     Print$="YES"
900   ELSE
910     Print$="NO"
920   END IF
930   RETURN
940   ! ******** END OF GET RESPONSE SUBROUTINE ********
950   !
960   ! ******* RUN ID NUMBER SUBROUTINE *******
970   DIM Campaign$[1]
980   DIM Matrix$[1]
990   DIM Box_cont_temp$[3]
1000  DIM Cent_rod_temp$[3]
```

```
1010  Campaign$="1"
1020  Matrix$="1"
1030  PRINT "ENTER RUN ID NUMBER OR <Return> FOR PROMPTS"
1040  INPUT "",Run_id_no$
1050  IF Run_id_no$="" THEN
1060    Yes_no$="N"
1070    WHILE Yes_no$="N"
1080      DISP "Enter Test Campaign Number (Default = 1)";
1090      LINPUT "",Campaign$
1100      IF Campaign$="" THEN Campaign$="1"
1110      DISP "Enter Matrix Number (Default = 1)";
1120      LINPUT "",Matrix$
1130      IF Matrix$="" THEN Matrix$="1"
1140      Environment$=""
1150      Err=0
1160      WHILE Environment$<>"N" AND Environment$<>"X" AND Environment$<>"A" AND Environment$<>"H"
1170        IF Err=1 THEN
1180          PRINT " MUST BE AN 'N', AN 'X', AN 'H' OR AN 'A'  ... RE-ENTER DATA"
1190        END IF
1200        Err=1
1210        DISP "Enter The Gas Environment -- (A)rgon, (N)itrogen,(H)elium, or X = AIR";
1220        LINPUT "",Environment$
1230        Environment$=UPC$(Environment$)
1240        IF LEN(Environment$)>1 THEN
1250          IF Environment$="NITROGEN" THEN
1260            Environment$="N"
1270          ELSE
1280            IF Environment$="HELIUM" THEN Environment$="H"
1290            IF Environment$="ARGON" THEN Environment$="A"
1300            IF Environment$="AIR" THEN Environment$="X"
1310          END IF
1320        END IF
1330      END WHILE
1340      Err=0
1350      Pressure$=""
1360      WHILE Pressure$<>"0" AND Pressure$<>"P" AND Pressure$<>"V"
1370        IF Err=1 THEN
1380          PRINT "YOU MUST ENTER A '0' FOR ZERO PSIG (Atmospheric Press.)"
1390          PRINT " A 'P' FOR POSITIVE PRESSURE ( > Atmospheric Press.)"
1400          PRINT " OR A 'V' FOR VACUUM ... PLEASE RE-ENTER"
1410        END IF
1420        DISP "Enter Cask Pressure -- 0 = Zero Psig, P = Positive Press., V = Vacuum";
1430        LINPUT "",Pressure$
1440        Pressure$=UPC$(Pressure$)
1450        IF Pressure$="Z" THEN Pressure$="0"
```

```
1460        IF LEN(Pressure$)>1 THEN
1470          IF Pressure$="PRESSURE" OR Pressure$="PRESSURIZED" OR Pressure$="P
OSITIVE" THEN
1480            Pressure$="P"
1490          ELSE
1500            IF Pressure$="ZERO" OR Pressure$="ATMOSPHERE" OR Pressure$="ATMO
SPHERIC" THEN Pressure$="0"
1510            IF Pressure$="VACUUM" OR Pressure$="VACCUM" OR Pressure$="VACUME
" THEN Pressure$="V"
1520          END IF
1530        END IF
1540        Err=1
1550      END WHILE
1560      Err=0
1570      Box_cont_temp=500
1580      WHILE Box_cont_temp<0 OR Box_cont_temp>250
1590        IF Err=1 THEN
1600          PRINT " YOU MUST ENTER A NUMBER BETWEEN 0 AND 250 (Deg. C)"
1610        END IF
1620        Err=1
1630        DISP "Enter Box Control Temperature  (3 digit number)";
1640        LINPUT "",Box_cont_temp$
1650        IF Box_cont_temp$<>"XXX" THEN
1660          Box_cont_temp=VAL(Box_cont_temp$)
1670        ELSE
1680          Box_cont_temp=100
1690        END IF
1700      END WHILE
1710      DISP "Enter Central Heater Rod Set Temperature  (3 digit number)";
1720      LINPUT "",Cent_rod_temp$
1730      Run_id_no$=Campaign$&Matrix$&Environment$&Pressure$&Box_cont_temp$&Cen
t_rod_temp$
1740      PRINT "RUN ID NUMBER IS: ";Run_id_no$
1750      LINPUT "IS THAT CORRECT",In$
1760      ENTER In$;Yes_no$
1770      Yes_no$=UPC$(Yes_no$)
1780    END WHILE
1790  END IF
1800  RETURN
2000 !
2010  ! ********* COPY DATA TO FILE ********
2020  IF Run_id_no$<>"" THEN
2030    CAT;SELECT Run_id_no$,COUNT Number_files,NO HEADER
2040    Number_files=Number_files+1
2050    Filename$=Run_id_no$&"."&VAL$(Number_files)
2060  ELSE
2070    Filename$=DATE$(TIMEDATE)
2080    Filename$=Filename$[1,2]&Filename$[4,6]&Filename$[8,11]
2090    CAT;SELECT Filename$,COUNT Number_files,NO HEADER
2100    Filename$=Filename$&"."&VAL$(Number_files+1)
2110  END IF
```

```
2120 DISP " ENTER FILE NAME FOR DATA STORAGE (DEFAULT IS: ";Filename$;")";
2130 INPUT "",File$
2140 IF File$<>"" THEN Filename$=File$
2150 PRINT "SAVING FILE AS: ";Filename$
2160 CREATE BDAT Filename$,12,128
2170 ASSIGN @Path1 TO Filename$
2180 OUTPUT @Path1;Run_id_no$
2190 OUTPUT @Path1;DATE$(TIMEDATE)
2200 OUTPUT @Path1;TIME$(TIMEDATE)
2210 OUTPUT @Path1;Volts
2220 OUTPUT @Path1;Amps
2230 OUTPUT @Path1;Watts_calc
2240 OUTPUT @Path1;Watts_disp
2250 OUTPUT @Path1;Temp1(*)
2260 OUTPUT @Path1;Temp2(*)
2270 OUTPUT @Path1;Temp3(*)
2280 OUTPUT @Path1;Temp4(*)
2290 OUTPUT @Path1;Temp5(*)
2300 OUTPUT @Path1;Temp_distr(*)
2310 OUTPUT @Path1;Bcbc1it
2320 OUTPUT @Path1;Bcbc3ib
2330 OUTPUT @Path1;Bcbc4il
2340 OUTPUT @Path1;Bcbc2ir
2350 OUTPUT @Path1;Bcbc5ile
2360 OUTPUT @Path1;Bcbc6iie
2361 OUTPUT @Path1;Ctemp_user
2362 OUTPUT @Path1;Atemp_user
2370 ASSIGN @Path1 TO *
2380 RETURN
5000 ! ********* PRINT TEMPERATURE DISTRIBUTIONS *******
5010 DIM Disply$(1:8,1:8)[10]
5020 REAL Temp_distr(1:8,1:8)
5030 DISP "PLEASE ENTER AC VOLTS   ROD-V-3(ID)  - MULTIMETER";
5040 INPUT "",Volts
5050 DISP "PLEASE ENTER AMPERAGE  ROD-A-1(ID)  - AMPS = DISPLAY / 10";
5060 INPUT "",Amps
5070 Watts_calc=Volts*Amps
5080 DISP "PLEASE ENTER WATTS ROD-W-I(ID)";
5090 INPUT "",Watts_disp
5100 PRINT "PLEASE SUPPLY THE FOLLOWING BOX TEMPERATURES"
5110 DISP "TOP -- BCB-C-1(IT) (CHANNEL 1 - DIGITAL THERMOMETER) ";
5120 INPUT "",Bcbc1it
5130 DISP " BOTTOM -- BCB-C-3(IB) (CHANNEL 4 - DIGITAL THERMOMETER) ";
5140 INPUT "",Bcbc3ib
5150 DISP "LEFT -- BCB-C-4(IL) (CHANNEL 3 - DIGITAL THERMOMETER)";
5160 INPUT "",Bcbc4il
5170 DISP " RIGHT -- BCB-C-2(IR) (CHANNEL 2 - DIGITAL THERMOMETER) ";
5180 INPUT "",Bcbc2ir
5190 DISP ""
```

```
5200  PRINT " PLEASE SUPPLY THE BOX CONTROL TEMPERATURES"
5210  DISP "ENTER BCB-C-5(ILE) (CHANNEL 10 - DIGITAL THERMOMETER)";
5220  INPUT "",Bcbc5ile
5230  DISP "ENTER BCB-C-6(IIE) (CHANNEL 6 - DIGITAL THERMOMETER)";
5240  INPUT "",Bcbc6iie
5250  DISP "ENTER ACTUAL CONTROL ROD TEMPERATURE (CH 7 DIGITAL THERMOMETER)";
5260  INPUT "",Ctemp_user
5270  DISP "ENTER ACTUAL ALARM ROD TEMPERATURE (CH 8 DIGITAL THERMOMETER)";
5280  INPUT "",Atemp_user
5290  PRINT ""
5300  PRINT "...................... THANK YOU ........................."
5310  Temp_distr(4,4)=DROUND(Temp5(14),4)   !C - TEMP
5320  Temp_distr(5,5)=DROUND(Temp5(13),4)   !A - TEMP
5330  Ctr=-1
5340  FOR Row=1 TO 2
5350    FOR Col=1 TO 8
5360      Temp_distr(Row,Col)=DROUND(Temp1(Col+Ctr),4)
5370    NEXT Col
5380    Ctr=Ctr+8
5390  NEXT Row
5400  Row=3
5410  Ctr=15
5420  FOR Col=1 TO 4
5430    Temp_distr(Row,Col)=DROUND(Temp1(Col+Ctr),4)
5440  NEXT Col
5450  Temp_distr(3,5)=DROUND(Temp1(17),4)
5460  Ctr=-5
5470  FOR Col=6 TO 8
5480    Temp_distr(Row,Col)=DROUND(Temp2(Col+Ctr),4)
5490  NEXT Col
5500  Ctr=3
5510  Row=4
5520  FOR Col=1 TO 3
5530    Temp_distr(Row,Col)=DROUND(Temp2(Col+Ctr),4)
5540  NEXT Col
5550  Temp_distr(4,5)=DROUND(Temp3(4),4)
5560  Row=4
5570  Ctr=1
5580  FOR Col=6 TO 8
5590    Temp_distr(Row,Col)=DROUND(Temp2(Col+Ctr),4)
5600  NEXT Col
5610  Row=5
5620  Ctr=-1
5630  FOR Col=1 TO 4
5640    Temp_distr(Row,Col)=DROUND(Temp3(Col+Ctr),4)
5650  NEXT Col
5660  Row=5
5670  Ctr=-1
5680  FOR Col=6 TO 8
5690    Temp_distr(Row,Col)=DROUND(Temp3(Col+Ctr),4)
5700  NEXT Col
```

```
5710  Ctr=7
5720  Row=6
5730  FOR Col=1 TO 8
5740    Temp_distr(Row,Col)=DROUND(Temp3(Col+Ctr),4)
5750  NEXT Col
5760  Row=7
5770  Ctr=15
5780  FOR Col=1 TO 4
5790    Temp_distr(Row,Col)=DROUND(Temp3(Col+Ctr),4)
5800  NEXT Col
5810  Row=7
5820  Ctr=-5
5830  FOR Col=5 TO 8
5840    Temp_distr(Row,Col)=DROUND(Temp4(Col+Ctr),4)
5850  NEXT Col
5860  Row=8
5870  Ctr=3
5880  FOR Col=1 TO 8
5890    Temp_distr(Row,Col)=DROUND(Temp4(Col+Ctr),4)
5900  NEXT Col
5910  ! ** PRINT RESULTS **
5920  PRINTER IS PRT
5930  PRINT CHR$(27);"(s1B";TAB(30);"TEMPERATURE DISTRIBUTION";CHR$(27);"(s0B"
5940  PRINT ""
5950  PRINT DATE$(TIMEDATE)
5960  PRINT TIME$(TIMEDATE)
5970  PRINT "RUN ID. NO. ";Run_id_no$
5980  PRINT "VOLTAGE (V) ";Volts
5990  PRINT "CURRENT (A) ";Amps
6000  PRINT "POWER (W) - DISPLAY ";Watts_disp
6010  PRINT "POWER (W) - CALCULATED ";Watts_calc
6020  PRINT ""
6030  PRINT ""
6040  FOR Row=1 TO 8
6050    FOR Col=1 TO 8
6060      Disply$(Row,Col)=VAL$(Temp_distr(Row,Col))
6070      IF VAL(Disply$(Row,Col))>1000 THEN
6080        Disply$(Row,Col)="---"
6090      END IF
6100      Disply$(3,2)="---"
6110      PRINT TAB(Col*8);Disply$(Row,Col);
6120    NEXT Col
6130    PRINT ""
6140    PRINT ""
6150  NEXT Row
6160  PRINT ""
```

```
6170  PRINT CHR$(27);"(s1B";TAB(34);CHR$(27);"&dD";"BOX TEMPERATURES";CHR$(27);"
(s0B";CHR$(27);"&d@"
6180  PRINT ""
6190  PRINT TAB(36);"TOP"
6200  PRINT ""
6210  PRINT TAB(36);DROUND(Temp2(17),4)
6220  PRINT TAB(8);RPT$("-",28);Bcbc1it;TAB(44);RPT$("-",24)
6230  PRINT TAB(8);"+";TAB(36);DROUND(Temp5(9),4);TAB(68);"+"
6240  PRINT TAB(8);"+";TAB(36);DROUND(Temp2(19),4);TAB(68);"+"
6250  PRINT TAB(8);"+";TAB(36);DROUND(Temp5(18),4);TAB(68);"+"
6260  FOR I=1 TO 2
6270    PRINT TAB(8);"+";TAB(68);"+"
6280  NEXT I
6290  PRINT TAB(8);DROUND(Temp5(3),4);TAB(65);DROUND(Temp5(0),4)
6300  PRINT TAB(8);DROUND(Temp5(4),4);TAB(65);DROUND(Temp5(1),4)
6310  PRINT "RIGHT";TAB(8);Bcbc2ir;TAB(65);Bcbc4il;TAB(72);"LEFT"
6320  PRINT TAB(8);DROUND(Temp5(5),4);TAB(65);DROUND(Temp5(2),4)
6330  PRINT TAB(8);DROUND(Temp5(17),4);TAB(65);DROUND(Temp5(16),4)
6340  FOR I=1 TO 2
6350    PRINT TAB(8);"+";TAB(68);"+"
6360  NEXT I
6370  PRINT TAB(8);"+";TAB(36);DROUND(Temp4(19),4);TAB(68);"+"
6380  PRINT TAB(8);"+";TAB(36);DROUND(Temp4(18),4);TAB(68);"+"
6390  PRINT TAB(8);RPT$("-",28);Bcbc3ib;TAB(44);RPT$("-",24)
6400  PRINT TAB(36);DROUND(Temp4(17),4)
6410  PRINT TAB(36);DROUND(Temp5(15),4)
6420  PRINT ""
6430  PRINT TAB(38);"BOTTOM"
6440  PRINT ""
6450  PRINT ""
6460  PRINT TAB(10);CHR$(27);"&dD";"VESSEL";CHR$(27);"&d@";TAB(38);CHR$(27);"&dD
";"LEAD END";CHR$(27);"&d@";TAB(63);CHR$(27);"&dD";"INTEGRAL END";CHR$(27);"&d@"
6470  PRINT TAB(10);DROUND(Temp5(6),4);TAB(30);DROUND(Temp4(14),4);TAB(50);DROUN
D(Temp2(10),4)
6480  PRINT TAB(10);DROUND(Temp5(7),4);TAB(30);DROUND(Temp4(13),4);TAB(50);DROUN
D(Temp2(11),4);TAB(60);"'C' TEMP = ";Ctemp_user
6490  PRINT TAB(10);DROUND(Temp5(10),4);TAB(30);DROUND(Temp4(15),4);TAB(50);DROU
ND(Temp2(12),4);TAB(60);"'A' TEMP = ";Atemp_user
6500  PRINT TAB(10);DROUND(Temp5(8),4);TAB(30);Bcbc5ile;TAB(50);DROUND(Temp2(13)
,4)
6510  PRINT TAB(10);DROUND(Temp5(19),4);TAB(50);Bcbc6iie
6520  PRINT CHR$(12)                          ! FORM FEED
6530  PRINTER IS CRT
6540  RETURN
6550  END
```

APPENDIX E

TEST DATA

This appendix contains the Test Data collected on the experimental apparatus.

The Test Data is presented in the following order:

E.1 Debugging Phase

This section of Appendix E contains the Test Data collected on the experimental apparatus during the Debugging Phase. This test data was collected prior to May 7, 1991. The testing was performed at atmospheric pressure (0 psig) in air at 10 different Heater Rod power levels with the controlling temperature ranging from 40°C to 250°C without the Boundary Condition Box side or end heaters operating and 5 different Heater Rod power levels with the controlling temperature ranging from 70°C to 250°C with the Boundary Condition Box end heaters operating. A Debugging Phase Campaign Summary follows:

Vessel Pressure (psig)	Fill Gas	Box Temperature (deg C)	Central Heater Rod Temperature (deg C)	Run I.D. No.	Date Completed
0 psig	Air	Not	40	11X0XXX040	04/30/91
		Controlled	50	11X0XXX050	04/30/91
			75	11X0XXX075	05/01/91
			100	11X0XXX100	04/22/91
			125	11X0XXX125	05/01/91
			150	11X0XXX150	04/25/91
			175	11X0XXX175	05/02/91
			200	11X0XXX200	04/28/91
			225	11X0XXX225	05/02/91
			250	11X0XXX250	04/29/91
0 psig	Air	Guard (end)	70	11X0XXX070E	05/04/91
		Heaters	80	11X0XXX080E	05/06/91
		Controlled by	90	11X0XXX090E	05/06/91
		Position 2-7	225	11X0XXX225E	05/02/91
			250	11X0XXX250E	05/04/91

Date: April 30, 1991
Time: 17:24:19

Run ID No. 11X0XXX040

Voltage:	10.3 Volts	Fill Gas:	Air
Current:	0.40 Amps	Pressure:	0 psig
Power:	4.12 Watts		

Vessel Temperature: Box End - 27.5 deg C
TC End - 28.4 deg C

Heater Rod Temperature Distribution

38.3	39.4	40.1	40.5	40.3	40.1	39.3	38.0
38.9	40.6	41.5	41.9	41.9	41.4	40.5	38.9
39.4	---	42.1	42.6	42.6	42.1	41.1	39.4
39.3	40.9	41.9	42.6	42.4	41.9	40.9	39.3
39.2	40.7	41.6	41.9	42.1	41.6	40.7	38.9
38.6	40.0	40.7	41.1	41.1	40.7	39.9	38.8
37.9	39.1	39.7	39.8	39.8	39.5	38.9	37.9
36.9	37.6	37.9	38.1	38.1	37.9	37.4	37.1

Box Temperature Distribution

Top 34.36 (epoxy)

Right 34.18 (epoxy) Left 33.97 (epoxy)

Bottom 33.96 (epoxy)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	38.16	39.82	41.37	40.8	38.92

Date: April 30, 1991
Time: 23:22:37

Run ID No. 11X0XXX050

Voltage:	11.9 Volts	Fill Gas:	Air
Current:	0.51 Amps	Pressure:	0 psig
Power:	6.07 Watts		

Vessel Temperature: Box End - 28.2 deg C
TC End - 29.3 deg C

Heater Rod Temperature Distribution

45.9	48.2	49.4	49.9	49.7	49.3	47.8	45.7
47.1	50.0	51.7	52.3	52.3	51.5	49.7	46.8
47.4	---	52.2	53.0	53.2	52.1	50.4	47.3
47.1	50.0	51.8	52.7	52.5	51.8	50.1	47.1
46.7	49.4	50.9	51.6	51.7	50.8	49.3	46.5
45.7	48.0	49.3	49.9	49.9	49.4	48.1	45.8
44.6	46.4	47.4	47.7	47.7	47.1	46.3	44.6
42.9	43.9	44.6	44.8	44.7	44.4	43.7	42.9

Box Temperature Distribution

Top 38.86 (epoxy)

Right 38.42 (epoxy) Left 38.08 (epoxy)

Bottom 37.87 (epoxy)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	45.58	48.99	51.02	49.7	46.74

Date: May 1, 1991
Time: 08:39:58

Run ID No. 11X0XXX075

Voltage:	21.5 Volts	Fill Gas:	Air
Current:	0.95 Amps	Pressure:	0 psig
Power:	20.42 Watts		

Vessel Temperature: Box End - 29.4 deg C
TC End - 31.6 deg C

Heater Rod Temperature Distribution

65.9	70.3	72.6	73.4	73.3	72.6	69.7	65.4
68.1	73.6	76.7	77.9	78.1	76.5	73.2	67.6
68.4	---	77.4	78.9	79.1	77.2	74.1	68.1
67.4	73.2	76.4	77.9	77.7	76.3	73.1	67.5
66.6	71.7	74.4	75.5	75.5	74.2	71.6	66.2
64.7	68.7	71.2	72.4	72.4	71.5	68.9	64.7
62.3	65.8	67.7	68.1	68.1	67.1	65.6	62.4
59.3	60.9	61.9	62.4	62.3	61.9	60.6	59.3

Box Temperature Distribution

Top 50.78 (epoxy)

Right 50.10 (epoxy)

Left 49.61 (epoxy)

Bottom 49.54 (epoxy)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	65.58	71.31	74.89	72.3	65.83

Date: April 22, 1991
Time: 14:34:09

Run ID No. 11X0XXX100

Voltage:	34.8 Volts	Fill Gas:	Air
Current:	1.37 Amps	Pressure:	0 psig
Power:	47.68 Watts		

Vessel Temperature: Box End - 30.2 deg C
TC End - 34.1 deg C

Heater Rod Temperature Distribution

84.8	91.2	94.4	95.3	95.3	94.4	90.4	84.3
87.9	96.2	100.4	101.8	102.4	99.8	95.4	87.4
88.1	---	101.3	103.5	103.8	101.1	96.7	87.8
87.1	95.2	99.6	102.1	101.9	99.6	95.7	87.5
85.5	92.9	96.8	98.9	98.8	96.7	93.1	84.8
82.7	89.0	92.2	94.4	94.1	92.6	89.6	83.5
79.8	84.4	87.5	87.7	87.7	87.1	84.3	80.2
75.9	77.3	78.9	80.3	79.7	79.1	77.2	75.7

Box Temperature Distribution

Top 62.33 (epoxy)

Right 61.11 (epoxy) Left 61.04 (epoxy)

Bottom 60.25 (epoxy)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	84.28	91.89	97.43	95.8	83.89

Date: May 1, 1991
Time: 17:36:15

Run ID No. 11X0XXX125

Voltage:	36.7 Volts	Fill Gas:	Air
Current:	1.59 Amps	Pressure:	0 psig
Power:	58.35 Watts		

Vessel Temperature: Box End - 31.9 deg C
TC End - 35.4 deg C

Heater Rod Temperature Distribution

104.6	112.5	116.8	118.0	118.0	116.7	111.4	103.6
108.9	119.1	124.9	126.9	127.2	124.4	118.2	107.7
109.2	---	126.5	129.1	129.3	125.8	120.0	108.9
107.7	118.7	124.6	127.5	126.8	125.5	118.6	108.0
106.3	115.9	121.3	123.3	123.2	120.9	115.6	105.3
102.6	110.6	115.2	117.4	117.4	115.4	110.8	102.6
98.2	104.9	108.2	109.3	109.3	107.5	104.6	98.6
92.5	95.4	97.6	98.4	98.2	97.3	94.8	92.4

Box Temperature Distribution

Top 76.17 (epoxy)

Right 74.00 (epoxy) Left 73.58 (epoxy)

Bottom 73.04 (epoxy)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	104.2	115.0	112.0	116.7	105.0

Date: April 25, 1991
Time: 09:32:54

Run ID No. 11X0XXX150

Voltage:	55.3 Volts	Fill Gas:	Air
Current:	2.19 Amps	Pressure:	0 psig
Power:	121.12 Watts		

Vessel Temperature: Box End - 37.8 deg C
TC End - 32.9 deg C

Heater Rod Temperature Distribution

124.3	134.2	139.2	140.8	140.6	139.1	132.7	123.3
129.9	142.5	149.3	151.7	151.9	148.8	141.2	128.7
130.7	---	151.7	154.6	154.9	151.3	144.5	130.9
129.0	142.5	149.7	152.9	153.2	149.6	142.6	129.3
127.3	139.9	146.2	149.1	148.7	145.7	139.4	126.4
122.8	133.3	138.7	141.7	141.5	139.0	133.6	123.1
117.2	126.1	130.3	131.5	131.7	129.3	125.4	117.6
110.2	113.9	116.8	117.9	117.7	116.6	113.0	109.8

Box Temperature Distribution

Top 88.58 (epoxy)

Right 86.55 (epoxy) Left 85.90 (epoxy)

Bottom 85.55 (epoxy)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	122.6	136.3	145.2	140.2	125.1

Date: May 2, 1991
Time: 00:10:57

Run ID No. 11X0XXX175

Voltage:	59.7 Volts	Fill Gas:	Air
Current:	2.34 Amps	Pressure:	0 psig
Power:	139.7 Watts		

Vessel Temperature: Box End - 41.2 deg C
TC End - 34.5 deg C

Heater Rod Temperature Distribution

143.4	154.6	160.4	162.5	162.1	160.4	153.2	142.2
150.4	164.8	172.9	175.8	176.4	172.4	163.7	148.9
151.7	---	176.3	180.1	180.4	175.2	167.1	151.2
149.9	166.0	174.8	179.0	178.1	174.6	166.3	150.8
148.5	162.8	170.7	173.7	173.7	170.3	162.3	147.2
143.6	155.6	162.6	165.9	166.1	162.8	155.8	143.8
137.1	147.6	152.9	154.4	154.4	151.6	146.9	137.8
128.7	133.4	136.9	138.4	138.1	136.7	132.5	128.4

Box Temperature Distribtion

Top 102.0 (epoxy)

Right 99.88 (epoxy)

Left 99.10 (epoxy)

Bottom 98.60 (epoxy)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	142.7	158.5	170.8	163.3	147.7

Date: April 28, 1991
Time: 13:52:51

Run ID No. 11X0XXX200

Voltage:	72.2 Volts	Fill Gas:	Air
Current:	2.85 Amps	Pressure:	0 psig
Power:	205.77 Watts		

Vessel Temperature: Box End - 45.3 deg C
TC End - 37.2 deg C

Heater Rod Temperature Distribution

162.5	175.1	181.8	184.3	183.6	181.7	173.5	161.3
170.7	187.1	196.3	199.4	200.5	195.4	186.1	169.0
172.7	---	200.7	204.9	205.4	199.3	190.4	172.6
171.9	189.6	199.6	204.0	203.3	199.6	189.7	171.7
169.7	186.1	195.6	199.2	198.9	194.8	185.7	168.1
164.3	178.4	186.4	190.3	190.6	186.8	178.5	164.5
157.2	169.5	175.9	177.6	177.6	174.6	168.7	157.8
148.0	153.4	157.5	159.1	159.8	157.5	152.6	147.7

Box Temperature Distribution

Top 117.4 (epoxy)

Right 114.6 (epoxy) Left 113.7 (epoxy)

Bottom 113.1 (epoxy)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	161.2	178.7	193.3	186.6	168.2

Date: May 2, 1991
Time: 10:17:06

Run ID No. 11X0XXX225

Voltage:	77.1 Volts	Fill Gas:	Air
Current:	3.12 Amps	Pressure:	0 psig
Power:	240.55 Watts		

Vessel Temperature: Box End - 47.8 deg C
TC End - 38.5 deg C

Heater Rod Temperature Distribution

181.6	195.4	202.5	205.6	204.7	202.7	193.8	180.3
191.1	209.4	219.4	223.2	223.7	218.9	208.1	189.5
194.0	---	225.3	230.1	230.4	224.1	213.7	193.6
192.8	213.6	225.1	230.1	229.1	224.7	213.9	193.6
191.8	210.7	221.4	225.2	225.3	220.8	210.4	190.3
186.2	202.5	211.4	216.4	216.7	212.2	202.5	186.1
178.2	192.7	199.9	202.2	202.3	198.4	191.9	179.0
167.6	174.6	179.7	181.3	181.3	179.4	173.2	167.3

Box Temperature Distribution

Top 132.5 (epoxy)

Right 129.6 (epoxy) Left 128.3 (epoxy)

Bottom 128.1 (epoxy)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	178.6	199.1	216.3	210.2	190.5

Date: April 29, 1991
Time: 19:26:24

Run ID No. 11X0XXX250

Voltage:	86.5 Volts	Fill Gas:	Air
Current:	3.46 Amps	Pressure:	0 psig
Power:	299.29 Watts		

Vessel Temperature: Box End - 52.3 deg C
TC End - 41.2 deg C

Heater Rod Temperature Distribution

201.5	216.6	224.5	227.8	226.8	224.8	215.2	200.3
212.4	232.3	243.1	247.2	247.7	242.6	231.1	210.6
215.8	---	250.1	255.1	255.7	248.8	237.3	215.2
214.7	237.6	250.2	255.7	254.6	249.8	238.0	215.8
214.1	234.9	246.6	251.1	250.9	246.2	234.4	212.1
208.1	226.4	236.9	241.7	242.0	236.9	226.2	207.7
199.3	215.7	223.8	226.3	226.6	222.2	214.7	200.1
187.5	195.3	201.2	203.6	203.2	201.1	194.0	187.1

Box Temperature Distribution

Top 148.1 (epoxy)

Right 143.9 (epoxy) Left 142.8 (epoxy)

Bottom 140.0 (epoxy)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	200.2	221.3	241.5	233.5	213.7

Date: May 4, 1991
Time: 20:56:51

Run ID No. 11X0XXX070E

Voltage:	19.46 Volts	Fill Gas:	Air
Current:	0.85 Amps	Pressure:	0 psig
Power:	16.54 Watts		

Vessel Temperature: Box End - 30.4 deg C
TC End - 28.6 deg C

Heater Rod Temperature Distribution

62.4	66.4	68.4	69.3	69.1	68.4	65.9	61.9
64.5	69.4	72.3	73.3	73.4	72.1	69.0	63.8
64.6	---	72.9	74.2	74.3	72.6	69.8	64.5
63.8	69.1	72.0	73.4	73.1	71.9	69.1	63.9
63.0	67.7	70.3	71.2	71.3	70.1	67.6	62.8
61.3	65.1	67.3	68.4	68.3	67.4	65.3	61.3
59.2	62.3	64.1	64.7	64.6	63.7	62.3	59.3
56.6	57.8	58.9	59.4	59.3	58.8	57.7	56.3

Box Temperature Distribution

Top 47.8 (epoxy)

Right 47.4 (epoxy) Left 47.2 (epoxy)

Bottom 46.3 (epoxy)

End of Heater Rod Temperature Distribution

Postion	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	63.18	67.35	70.57	68.1	62.45

Date: May 6, 1991
Time: 08:38:10

Run ID No. 11X0XXX080E

Voltage:	20.6 Volts	Fill Gas:	Air
Current:	0.92 Amps	Pressure:	0 psig
Power:	18.95 Watts		

Vessel Temperature: Box End - 32.8 deg C
TC End - 30.4 deg C

Heater Rod Temperature Distribution

70.3	74.7	77.0	77.9	77.9	77.1	74.1	69.8
72.6	78.1	81.3	82.4	82.7	81.1	77.6	71.9
72.7	---	82.1	83.6	83.8	82.0	78.6	72.7
71.9	77.9	81.0	82.8	82.2	80.9	77.8	72.1
71.1	76.2	79.1	80.3	80.2	78.9	76.1	70.6
69.0	73.2	75.7	76.9	76.9	75.9	73.4	69.1
66.7	70.2	72.0	72.6	72.6	71.6	70.0	66.9
63.6	65.2	66.4	66.8	66.7	66.3	64.9	63.6

Box Temperature Distribution

Top 53.9 (epoxy)

Right 53.4 (epoxy) Left 53.2 (epoxy)

Bottom 52.0 (epoxy)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	72.49	77.97	81.81	81.3	71.88

Date: May 6, 1991
Time: 20:08:35

Run ID No. 11XCXXX090E

Voltage:	21.2 Volts	Fill Gas:	Air
Current:	0.95 Amps	Pressure:	0 psig
Power:	20.14 Watts		

Vessel Temperature: Box End - 34.8 deg C
TC End - 31.5 deg C

Heater Rod Temperature Distribution

79.3	84.4	86.6	87.6	87.5	86.3	83.3	78.6
81.8	88.1	91.1	92.2	92.1	90.4	86.8	80.6
81.5	---	91.7	93.2	93.2	91.3	87.8	81.1
80.7	87.1	90.4	92.3	91.7	90.3	86.9	80.6
79.6	85.3	88.4	89.6	89.6	88.2	85.0	79.1
77.6	82.2	84.9	86.1	86.1	84.8	82.1	77.5
75.1	78.8	80.9	81.3	81.3	80.3	78.5	75.2
71.7	73.3	74.7	75.1	74.9	74.4	72.9	71.5

Box Temperature Distribution

Top 60.9 (epoxy)

Right 60.1 (epoxy) Left 59.9 (epoxy)

Bottom 58.5 (epoxy)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	80.38	87.18	92.07	88.9	80.89

Date: May 2, 1991
Time: 22:16:10

Run ID No. 11X0XXX225E

Voltage:	55.9 Volts	Fill Gas:	Air
Current:	2.32 Amps	Pressure:	0 psig
Power:	129.69 Watts		

Vessel Temperature: Box End - 54.8 deg C
TC End - 42.5 deg C

Heater Rod Temperature Distribution

188.2	199.3	204.7	207.6	206.7	204.8	197.9	187.3
196.9	212.3	220.2	223.1	222.9	218.7	210.4	195.2
199.4	---	225.8	229.4	229.5	224.8	216.3	198.9
199.4	217.5	226.4	230.3	229.5	225.3	216.1	199.1
198.3	214.2	223.1	226.8	226.8	222.5	214.1	196.9
193.7	207.8	216.2	219.3	218.9	215.3	206.7	193.3
187.8	198.7	204.9	207.2	206.9	204.3	198.3	187.7
179.9	183.9	188.6	190.2	189.8	188.3	184.3	178.0

Box Temperature Distribution

Top 145.3 (epoxy)

Right 143.2 (epoxy) Left 142.4 (epoxy)

Bottom 138.5 (epoxy)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	191.9	211.1	228.7	223.9	204.8

Date: May 4, 1991
Time: 01:36:36

Run ID No. 11X0XXX250E

Voltage:	68.9 Volts	Fill Gas:	Air
Current:	2.80 Amps	Pressure:	0 psig
Power:	192.92 Watts		

Vessel Temperature: Box End - 59.3 deg C
TC End - 45.2 deg C

Heater Rod Temperature Distribution

207.7	220.2	226.1	229.2	228.3	226.4	218.7	206.9
217.8	234.8	243.3	246.5	246.6	242.0	232.7	215.9
221.1	---	249.9	254.2	254.3	248.9	239.6	220.5
221.1	241.0	251.5	255.6	254.9	250.2	239.9	221.2
220.4	238.1	248.1	252.3	252.4	247.6	238.0	218.9
215.5	231.4	240.9	244.4	244.1	240.2	230.4	215.0
208.8	221.6	228.9	231.3	231.2	228.1	221.2	208.8
199.8	204.9	210.3	212.0	211.9	210.0	205.2	197.8

Box Temperature Distribution

Top 160.0 (epoxy)

Right 158.2 (epoxy) Left 157.1 (epoxy)

Bottom 152.7 (epoxy)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	254.7	231.2	250.4	246.6	225.5

E.2 Atmospheric Pressure Test Data #1

This section of Appendix E contains the Test Data collected on the experimental apparatus at atmospheric pressure in air at 10 different Heater Rod power levels with the controlling temperature ranging from 70°C to 250°C with Boundary Condition Box end heaters operating. (Note: This data set was not analyzed because the error could not be conveniently bracketed.) A Campaign Summary follows:

Vessel Pressure (psig)	Fill Gas	Box Temperature (deg C)	Central Heater Rod Temperature (deg C)	Run I.D. No.	Date Completed
0 psig	Air	Guard (end)	70	11X0XXX070E	05/07/91
		Heaters	80	11X0XXX080E	05/08/91
		Controlled by	90	11X0XXX090E	05/09/91
		Position 2-7	100	11X0XXX100E	05/10/91
			125	11X0XXX125E	05/11/91
			150	11X0XXX150E	05/12/91
			175	11X0XXX175E	05/12/91
			200	11X0XXX200E	05/13/91
			225	11X0XXX225E	05/14/91
			250	11X0XXX250E	05/15/91

Date: May 7, 1991
Time: 23:11:46

Run ID No. 11X0XXX070E

Voltage:	16.7 Volts	Fill Gas:	Air
Current:	0.72 Amps	Pressure:	0 psig
Power:	12.024 Watts		

Vessel Temperature: Box End - 31.9 deg C
TC End - 28.5 deg C

Heater Rod Temperature Distribution

62.3	65.9	67.7	68.3	68.2	67.6	65.2	61.8
64.2	68.7	71.3	72.3	72.3	70.9	68.1	63.6
64.2	---	71.9	73.1	73.2	71.6	69.2	64.1
63.7	68.4	71.1	72.5	72.0	70.9	68.2	63.5
62.8	67.1	69.3	70.3	70.4	69.2	66.8	62.1
60.9	64.7	66.8	67.6	67.5	66.6	64.6	60.9
59.2	62.0	63.6	63.9	63.8	63.2	61.8	59.2
56.6	57.8	58.8	59.2	59.1	58.7	57.6	56.4

Box Temperature Distribution

Top 48.4(epoxy) 49.2(under htr)

Right 48.1(epoxy) 48.9(under htr) Left 48.1(epoxy) 48.9(under htr)

Bottom 46.9(epoxy) 47.9(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	62.55	67.27	67.86	68.2	62.73

Date: May 8, 1991
Time: 19:48:17

Run ID No. 11X0XXX080E

Voltage:	18.9 Volts	Fill Gas:	Air
Current:	0.85 Amps	Pressure:	0 psig
Power:	16.065 Watts		

Vessel Temperature: Box End - 33.6 deg C
TC End - 29.1 deg C

Heater Rod Temperature Distribution

71.2	75.4	77.6	78.3	78.3	77.4	74.9	70.7
73.4	78.9	81.8	82.9	82.8	81.3	78.1	72.8
73.6	---	82.4	83.8	83.8	82.1	79.2	73.3
72.7	78.3	81.4	82.8	82.4	81.1	78.1	72.6
71.6	76.7	79.2	80.4	80.4	78.9	76.4	71.2
69.8	73.9	76.4	77.6	77.2	76.1	73.6	69.8
67.3	70.7	72.4	72.9	72.9	72.1	70.6	67.4
64.6	66.1	67.1	67.4	67.3	66.9	65.7	64.4

Box Temperature Distribution

Top 54.8(epoxy) 55.9(under htr)

Right 54.4(epoxy) 55.4(under htr)

Left 54.4(epoxy) 55.4(under htr)

Bottom 52.7(epoxy) 54.1(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	72.19	78.41	81.04	79.2	72.57

Date: May 9, 1991
Time: 16:50:49

Run ID No. 11X0XXX090E

Voltage:	23.2 Volts	Fill Gas:	Air
Current:	1.07 Amps	Pressure:	0 psig
Power:	24.824 Watts		

Vessel Temperature: Box End - 34.9 deg C
TC End - 29.2 deg C

Heater Rod Temperature Distribution

79.1	83.8	86.3	87.2	87.2	86.3	83.2	78.4
81.7	87.9	91.3	92.6	92.7	90.8	87.1	80.8
81.8	---	92.1	93.7	93.9	91.8	88.5	81.7
81.2	87.9	91.2	92.9	92.6	90.7	87.2	80.8
79.9	85.6	88.6	89.9	90.3	88.4	85.4	79.2
77.6	82.3	85.3	86.2	86.0	84.8	82.1	77.3
74.8	78.4	80.5	81.0	80.9	80.0	78.3	74.7
71.4	72.9	74.2	74.7	74.6	74.0	72.7	71.2

Box Temperature Distribution

Top 60.2(epoxy) 61.6(under htr)

Right 59.8(epoxy) 60.7(under htr) Left 59.6(epoxy) 61.0(under htr)

Bottom 57.8(epoxy) 59.3(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	81.42	88.09	93.13	88.9	80.97

Date: May 10, 1991
Time: 12:48:15

Run ID No. 11X0XXX100E

Voltage:	23.8 Volts	Fill Gas:	Air
Current:	1.04 Amps	Pressure:	0 psig
Power:	24.752 Watts		

Vessel Temperature: Box End - 37.2 deg C
TC End - 30.3 deg C

Heater Rod Temperature Distribution

87.9	92.9	95.6	96.6	96.6	95.6	92.3	87.1
90.7	97.6	101.3	102.5	102.5	100.7	96.7	89.8
90.8	---	102.3	103.9	104.1	102.0	98.4	91.2
90.6	98.1	101.7	103.0	102.5	100.9	97.0	90.0
88.7	95.0	98.5	99.9	100.2	98.2	94.7	87.8
86.0	91.3	94.4	95.8	95.6	94.3	91.3	85.8
83.3	87.3	89.5	90.1	90.1	88.9	86.9	83.1
79.3	81.0	82.8	83.1	82.9	82.3	80.7	79.1

Box Temperature Distribution

Top 66.7(epoxy) 68.1(under htr)

Right 65.9(epoxy) 67.3(under htr)

Left 65.8(epoxy) 67.4(under htr)

Bottom 63.7(epoxy) 65.7(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	90.34	97.89	103.3	100.8	90.26

Date: May 11, 1991
Time: 10:24:48

Run ID No. 11X0XXX125E

Voltage:	30.9 Volts	Fill Gas:	Air
Current:	1.24 Amps	Pressure:	0 psig
Power:	38.316 Watts		

Vessel Temperature: Box End - 40.3 deg C
TC End - 31.0 deg C

Heater Rod Temperature Distribution

107.6	114.4	117.9	119.1	119.0	117.9	113.3	106.7
111.8	121.1	125.8	127.4	127.2	124.7	119.5	110.6
111.8	---	127.3	129.4	129.5	126.7	121.7	111.9
111.2	120.9	125.9	127.8	127.1	125.2	119.9	110.6
108.7	117.4	122.2	123.9	124.1	121.6	117.0	107.8
105.6	112.8	117.0	118.8	118.5	116.8	112.5	105.4
101.8	107.6	110.7	111.5	111.5	110.3	107.6	102.2
97.8	99.4	101.4	102.2	102.1	101.3	99.8	96.9

Box Temperature Distribution

Top 79.9(epoxy) 81.7(under htr)

Right 78.6(epoxy) 80.3(under htr)   Left 78.3(epoxy) 80.6(under htr)

Bottom 75.5(epoxy) 78.1(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	108.7	118.9	124.1	123.2	109.8

Date: May 12, 1991
Time: 01:55:35

Run ID No. 11X0XXX150E

Voltage:	35.6 Volts	Fill Gas:	Air
Current:	1.53 Amps	Pressure:	0 psig
Power:	54.468 Watts		

Vessel Temperature: Box End - 46.2 deg C
TC End - 33.8 deg C

Heater Rod Temperature Distribution

128.1	136.2	140.1	141.7	141.4	139.9	135.0	127.2
133.6	144.4	149.8	151.6	151.4	148.4	142.6	131.8
133.9	---	151.9	154.2	154.4	151.2	145.5	133.9
132.9	144.5	150.3	152.3	151.6	149.6	143.4	132.2
130.3	140.8	146.2	148.2	148.6	145.7	140.1	129.1
126.6	135.3	140.3	142.7	142.3	140.1	135.0	126.4
121.9	129.3	133.1	134.1	134.1	132.4	129.0	122.5
116.8	119.3	122.0	123.1	122.8	121.8	119.3	116.1

Box Temperature Distribution

Top 95.1(epoxy) 98.2(under htr)

Right 94.2(epoxy) 96.3(under htr)

Left 93.7(epoxy) 96.7(under htr)

Bottom 89.9(epoxy) 93.6(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	130.3	142.6	150.5	147.1	133.1

Date: May 12, 1991
Time: 15:41:03

Run ID No. 11X0XXX175E

Voltage:	45.7 Volts	Fill Gas:	Air
Current:	1.79 Amps	Pressure:	0 psig
Power:	81.803 Watts		

Vessel Temperature: Box End - 52.0 deg C
TC End - 36.5 deg C

Heater Rod Temperature Distribution

147.2	156.4	161.1	163.1	162.5	161.0	155.1	146.3
153.3	165.9	172.3	174.7	174.6	171.3	164.2	151.8
154.5	---	175.4	178.6	178.8	174.8	168.1	154.6
154.3	168.1	175.2	178.4	177.8	174.0	166.8	153.7
152.7	164.8	171.4	174.5	174.8	171.0	164.7	151.7
148.7	159.3	165.4	167.8	167.1	164.5	158.2	148.3
143.7	151.3	155.7	157.3	157.1	155.6	151.1	143.3
137.6	139.4	143.0	143.8	143.7	142.7	140.1	135.3

Box Temperature Distribution

Top 109.5(epoxy) 113.9(under htr)

Right 109.0(epoxy) 111.6(under htr)

Left 108.6(epoxy) 111.8(under htr)

Bottom 103.7(epoxy) 108.3(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	149.9	163.2	141.4	170.9	154.2

Date: May 13, 1991
Time: 11:48:50

Run ID No. 11X0XXX200E

Voltage:	48.8 Volts	Fill Gas:	Air
Current:	1.92 Amps	Pressure:	0 psig
Power:	93.696 Watts		

Vessel Temperature: Box End - 59.5 deg C
TC End - 39.4 deg C

Heater Rod Temperature Distribution

168.9	179.0	183.7	186.0	185.4	183.7	177.5	168.1
176.3	189.9	196.8	199.2	198.9	195.3	187.9	174.3
177.7	---	200.8	204.0	204.2	199.9	192.6	177.4
177.6	193.2	200.9	204.0	203.3	199.8	191.5	176.9
176.1	189.6	196.9	200.4	200.4	196.6	189.2	174.7
171.8	183.9	190.6	193.2	192.6	189.7	182.6	171.3
166.4	175.0	180.2	182.0	181.8	179.8	174.8	165.9
159.5	162.2	166.3	167.4	167.0	165.9	162.9	157.5

Box Temperature Distribution

Top 129.2(epoxy) 134.8(under htr)

Right 128.2(epoxy) 131.9(under htr)

Left 127.7(epoxy) 132.0(under htr)

Bottom 121.9(epoxy) 127.7(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	173.1	189.2	204.6	199.7	180.9

Date: May 14, 1991
Time: 22:50:12

Run ID No. 11X0XXX225E

Voltage:	62.1 Volts	Fill Gas:	Air
Current:	2.42 Amps	Pressure:	0 psig
Power:	150.282 Watts		

Vessel Temperature: Box End - 63.9 deg C
TC End - 42.1 deg C

Heater Rod Temperature Distribution

188.1	199.5	205.1	207.8	207.1	205.1	198.0	187.2
196.8	212.5	220.4	223.3	223.2	219.0	210.4	194.8
199.2	---	225.6	229.4	229.5	224.7	216.3	198.8
198.9	217.3	226.2	229.9	229.3	225.0	215.8	198.7
197.7	213.6	222.5	226.7	226.5	221.9	213.3	196.3
193.1	207.1	215.7	218.6	218.2	214.5	206.0	192.4
187.0	197.8	204.0	206.3	206.2	203.4	197.4	186.9
179.1	182.9	187.7	189.1	188.8	187.5	183.5	177.1

Box Temperature Distribution

Top 143.4(epoxy) 149.9(under htr)

Right 142.9(epoxy) 147.0(under htr) Left 142.2(epoxy) 147.1(under htr)

Bottom 135.7(epoxy) 142.3(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	199.9	210.2	225.6	223.3	203.0

Date: May 15, 1991
Time: 12:31:52

Run ID No. 11X0XXX250E

Voltage:	79.6 Volts	Fill Gas:	Air
Current:	3.07 Amps	Pressure:	0 psig
Power:	244.372 Watts		

Vessel Temperature: Box End - 69.1 deg C
TC End - 44.5 deg C

Heater Rod Temperature Distribution

207.7	220.3	226.8	229.8	228.9	226.9	218.9	206.7
217.8	235.1	243.9	247.3	247.3	242.5	233.1	215.7
220.8	---	250.3	254.7	255.1	249.2	239.8	220.3
220.7	240.9	251.4	255.7	254.9	250.2	239.8	220.6
219.8	237.6	247.7	252.0	252.3	247.4	237.4	218.2
214.6	230.7	240.2	243.9	243.6	239.4	229.7	214.1
207.7	220.7	227.7	230.4	230.3	227.2	220.2	207.7
198.5	203.6	209.1	211.1	210.7	209.0	204.0	196.7

Box Temperature Distribution

Top 157.7(epoxy) 165.3(under htr)

Right 156.9(epoxy) 162.3(under htr)

Left 156.1(epoxy) 162.5(under htr)

Bottom 149.3(epoxy) 156.9(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	---	231.1	245.5	246.1	224.8

E.3 Atmospheric Pressure Test Data #2

This section of Appendix E contains the Test Data collected on the experimental apparatus at atmospheric pressure (0 psig) in air at 12 different Heater Rod power levels with the controlling temperature ranging from 70°C to 250°C without Boundary Condition Box side or end heaters operating. A Campaign Summary follows:

Vessel Pressure (psig)	Fill Gas	Box Temperature (deg C)	Central Heater Rod Temperature (deg C)	Run I.D. No.	Date Completed
0 psig	Air	Not Controlled	70	11X0XXX070	06/01/91
			75	11X0XXX075	05/23/91
			100	11X0XXX100	5/24 6/3
			125	11X0XXX125	05/24/91
			140	11X0XXX140	05/20/91
			150	11X0XXX150	5/27 6/4 6/5
			175	11X0XXX175	05/27/91
			190	11X0XXX190	05/20/91
			200	11X0XXX200	5/28 6/8
			225	11X0XXX225	05/28/91
			240	11X0XXX240	5/17 5/21
			250	11X0XXX250	5/21 5/29

Date: June 1, 1991
Time: 16:24:45

Run ID No. 11X0XXX070

Voltage:	28.66 Volts	Fill Gas:	Air
Current:	1.11 Amps	Pressure:	0 psig
Power:	31.813 Watts		

Vessel Temperature: Box End - 30.83 deg C
TC End - 28.33 deg C

Heater Rod Temperature Distribution

61.25	65.21	67.39	68.16	68.01	67.36	64.73	60.75
63.32	68.40	71.24	72.35	72.47	70.99	67.86	62.70
63.47	---	71.93	73.28	73.44	71.62	68.72	63.27
62.69	68.09	71.04	73.02	72.14	70.97	68.04	62.84
61.98	66.73	69.33	70.39	70.47	69.17	66.52	61.52
60.21	64.13	66.31	67.49	67.44	66.46	64.21	60.21
58.02	61.31	62.99	63.47	63.47	62.59	61.10	58.12
55.13	56.67	57.81	58.21	58.11	57.71	56.42	55.12

Box Temperature Distribution

Top 46.6(epoxy) 47.57(under htr)

Right 46.4(epoxy) 47.13(under htr)

Left 46.2(epoxy) 47.29(under htr)

Bottom 45.0(epoxy) 46.38(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	61.04	66.05	63.31	67.5	61.46

Date: May 23, 1991
Time: 23:05:03

Run ID No. 11X0XXX075

Voltage:	26.8 Volts	Fill Gas:	Air
Current:	1.51 Amps	Pressure:	0 psig
Power:	40.5 Watts		

Vessel Temperature: Box End - 31.6 deg C
TC End - 27.5 deg C

Heater Rod Temperature Distribution

65.1	69.44	71.82	72.64	72.49	71.81	68.9	64.49
67.85	72.95	76.0	77.24	77.37	75.7	72.32	66.66
67.44	---	76.77	78.56	78.42	76.62	73.33	67.34
66.69	72.59	75.86	77.71	77.06	75.76	72.56	66.81
65.94	71.14	73.98	75.11	75.42	73.77	70.86	65.33
63.91	68.2	70.59	71.9	71.85	70.71	68.26	63.9
61.43	65.07	66.91	67.37	67.53	66.54	64.91	61.64
58.41	60.04	61.28	61.68	61.6	61.18	59.68	58.34

Box Temperature Distribution

Top 48.9(epoxy) 49.87(under htr)

Right 48.8(epoxy) 49.34(under htr)

Left 48.4(epoxy) 49.58(under htr)

Bottom 47.1(epoxy) 49.14(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	65.07	70.37	67.65	72.0	65.22

Date: May 24, 1991
Time: 14:49:14

Run ID No. 11X0XXX100

Voltage:	37.7 Volts	Fill Gas:	Air
Current:	1.84 Amps	Pressure:	0 psig
Power:	69.4 Watts		

Vessel Temperature: Box End - 34.9 deg C
TC End - 30.8 deg C

Heater Rod Temperature Distribution

84.6	90.76	94.06	95.05	95.02	94.12	90.02	83.77
88.6	95.82	100.1	101.8	102.0	99.72	94.95	86.88
88.0	---	101.2	103.6	103.5	100.8	96.27	87.68
86.7	95.15	99.84	102.2	101.3	99.62	95.14	86.98
85.49	92.91	96.95	98.52	98.84	96.74	92.58	84.69
82.62	88.72	92.12	93.95	93.9	92.32	88.82	82.58
79.08	84.25	86.87	87.54	87.67	86.31	83.98	79.34
74.77	77.01	78.76	79.33	79.23	78.58	76.54	74.64

Box Temperature Distribution

Top 60.8(epoxy) 62.38(under htr)

Right 60.6(epoxy) 61.54(under htr)

Left 60.1(epoxy) 61.70(under htr)

Bottom 58.3(epoxy) 60.93(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	84.51	91.99	87.75	93.8	84.45

Date: June 3, 1991
Time: 18:10:32

Run ID No. 11X0XXX100

Voltage:	40.5 Volts	Fill Gas:	Air
Current:	1.58 Amps	Pressure:	0 psig
Power:	63.99 Watts		

Vessel Temperature: Box End - 34.8 deg C
TC End - 30.8 deg C

Heater Rod Temperature Distribution

84.98	91.21	94.54	95.52	95.51	94.57	90.46	84.21
88.36	96.26	100.6	102.3	102.5	100.3	95.44	87.31
88.47	---	101.7	103.8	104.0	101.2	96.73	88.15
87.19	95.65	100.2	103.0	101.9	100.1	95.58	87.38
85.92	93.41	97.46	99.05	99.29	97.24	93.11	85.2
83.1	89.24	92.66	94.47	94.4	92.87	89.37	83.05
79.58	84.73	87.36	88.1	88.12	86.76	84.47	79.81
75.14	77.43	79.19	79.83	79.71	79.04	77.01	75.1

Box Temperature Distribution

Top 60.9(epoxy) 62.66(under htr)

Right 60.7(epoxy) 61.86(under htr)

Left 60.2(epoxy) 62.06(under htr)

Bottom 58.3(epoxy) 60.58(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	84.53	92.43	87.58	94.3	84.75

Date: May 24, 1991
Time: 23:37:18

Run ID No. 11X0XXX125

Voltage:	47.7 Volts	Fill Gas:	Air
Current:	2.22 Amps	Pressure:	0 psig
Power:	105.894 Watts		

Vessel Temperature: Box End - 38.7 deg C
TC End - 33.3 deg C

Heater Rod Temperature Distribution

104.6	112.6	116.8	118.0	118.0	116.9	111.6	103.6
110.1	119.3	124.8	126.9	127.2	124.4	118.3	107.8
109.4	---	126.5	129.4	129.4	126.0	120.2	109.1
107.8	118.9	124.8	127.9	126.8	124.7	118.9	108.2
106.4	116.1	121.4	123.4	123.7	121.1	115.8	105.3
102.7	110.8	115.3	117.6	117.5	115.5	110.9	102.6
98.1	104.9	108.4	109.3	109.4	107.6	104.5	98.38
92.35	95.39	97.68	98.47	98.34	97.48	94.73	92.24

Box Temperature Distribution

Top 73.3(epoxy) 75.71(under htr)

Right 73.1(epoxy) 74.59(under htr)

Left 72.4(epoxy) 74.69(under htr)

Bottom 70.0(epoxy) 73.20(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	104.2	114.3	108.9	116.7	105.0

Date: May 20, 1991
Time: 10:10:49

Run ID No. 11X0XXX140

Voltage:	46.0 Volts	Fill Gas:	Air
Current:	1.85 Amps	Pressure:	0 psig
Power:	85.1 Watts		

Vessel Temperature: Box End - 38.9 deg C
TC End - 30.1 deg C

Heater Rod Temperature Distribution

115.0	124.0	128.7	130.2	130.1	128.8	123.0	114.0
120.4	131.8	138.1	140.4	140.8	137.6	130.6	118.9
120.8	---	140.2	143.4	143.5	139.6	133.3	120.7
119.4	131.9	138.7	142.7	141.3	138.6	132.0	119.9
118.0	129.3	135.4	137.6	137.8	135.0	128.9	116.9
113.9	123.3	128.5	131.2	131.2	128.8	123.5	113.9
108.7	116.8	120.9	122.0	122.1	120.1	116.5	109.2
102.2	105.6	108.4	109.5	109.3	108.3	105.1	102.1

Box Temperature Distribution

Top 79.6(epoxy) 82.38(under htr)

Right 79.1(epoxy) 80.96(under htr)

Left 78.3(epoxy) 81.01(under htr)

Bottom 75.6(epoxy) 78.91(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	114.2	126.1	120.5	130.4	116.4

Date: May 27, 1991
Time: 13:24:21

Run ID No. 11X0XXX150

Voltage:	58.0 Volts	Fill Gas:	Air
Current:	2.58 Amps	Pressure:	0 psig
Power:	149.64 Watts		

Vessel Temperature: Box End - 41.2 deg C
TC End - 34.6 deg C

Heater Rod Temperature Distribution

123.5	133.1	138.2	139.7	139.6	138.3	132.0	122.4
130.0	141.6	148.2	150.7	151.1	147.8	140.4	127.7
129.8	---	150.5	154.0	154.0	149.8	142.9	129.4
128.1	141.6	148.9	152.4	151.3	148.6	141.6	128.6
126.4	138.4	144.9	147.3	147.5	144.5	138.0	125.2
122.0	131.9	137.6	140.4	140.5	137.8	132.1	121.9
116.3	124.9	129.2	130.4	130.6	128.3	124.5	116.8
109.3	113.1	116.0	117.1	116.9	115.8	112.4	109.2

Box Temperature Distribution

Top 85.0(epoxy) 88.40(under htr)

Right 84.8(epoxy) 86.87(under htr) Left 83.9(epoxy) 86.82(under htr)

Bottom 80.9(epoxy) 85.15(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	122.8	135.4	129.2	139.1	124.6

Date: June 4, 1991
Time: 15:16:16

Run ID No. 11X0XXX150

Voltage:	60.8 Volts	Fill Gas:	Air
Current:	2.37 Amps	Pressure:	0 psig
Power:	144.096 Watts		

Vessel Temperature: Box End - 40.4 deg C
TC End - 33.3 deg C

Heater Rod Temperature Distribution

123.8	133.5	138.7	140.2	140.1	138.8	132.5	122.7
129.8	142.1	148.9	151.4	151.7	148.4	140.9	128.1
130.3	---	151.2	154.3	154.8	150.4	143.5	129.9
128.6	142.2	149.6	153.1	152.0	149.3	142.3	129.0
126.8	139.0	145.6	148.0	147.9	145.3	138.6	125.6
122.5	132.6	138.3	141.2	141.2	138.5	132.7	122.3
116.8	125.4	129.8	131.1	131.1	128.9	125.0	117.1
109.5	113.4	116.4	117.5	117.4	116.2	112.7	109.4

Box Temperature Distribution

Top 84.9(epoxy) 88.53(under htr)

Right 84.8(epoxy) 86.93(under htr) Left 83.7(epoxy) 87.03(under htr)

Bottom 80.8(epoxy) 84.91(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	122.8	135.8	129.1	139.7	125.1

Date: June 5, 1991
Time: 20:03:06

Run ID No. 11X0XXX150

Voltage:	61.4 Volts	Fill Gas:	Air
Current:	2.39 Amps	Pressure:	0 psig
Power:	146.746 Watts		

Vessel Temperature: Box End - 40.14 deg C
TC End - 33.22 deg C

Heater Rod Temperature Distribution

123.8	133.5	138.7	140.2	140.1	138.8	132.4	122.7
129.9	142.2	148.9	151.4	151.8	148.5	141.0	128.1
130.3	---	151.3	154.4	154.8	150.5	143.6	129.9
128.6	142.3	149.6	153.6	152.1	149.4	142.3	129.0
126.9	139.1	145.7	148.1	148.7	145.4	138.7	125.7
122.5	132.7	138.4	141.3	141.3	138.6	132.8	122.4
116.8	125.5	129.9	131.2	131.2	129.0	125.1	117.2
109.6	113.5	116.5	117.6	117.4	116.2	112.7	109.4

Box Temperature Distribution

Top 84.6(epoxy) 88.23(under htr)

Right 84.6(epoxy) 86.65(under htr)

Left 83.6(epoxy) 86.84(under htr)

Bottom 80.6(epoxy) 84.28(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	122.8	135.8	129.1	139.9	125.1

Date: May 27, 1991
Time: 21:51:20

Run ID No. 11X0XXX175

Voltage:	65.5 Volts	Fill Gas:	Air
Current:	2.85 Amps	Pressure:	0 psig
Power:	186.675 Watts		

Vessel Temperature: Box End - 44.5 deg C
TC End - 35.9 deg C

Heater Rod Temperature Distribution

143.9	155.0	160.9	162.8	162.6	161.1	153.8	142.7
151.8	165.4	173.1	176.1	176.6	172.6	164.0	149.2
152.0	---	176.5	180.6	180.6	175.6	167.4	151.6
150.2	166.3	175.0	179.2	177.8	174.7	166.3	150.9
148.6	162.9	170.7	173.6	173.8	170.3	162.3	147.1
143.5	155.5	162.4	165.8	165.8	162.6	155.7	143.5
136.9	147.4	152.6	154.2	154.3	151.6	146.9	137.5
128.6	133.3	137.0	138.3	138.1	136.7	132.4	128.4

Box Temperature Distribution

Top 98.9(epoxy) 103.2(under htr)

Right 98.7(epoxy) 101.3(under htr) Left 97.4(epoxy) 101.3(under htr)

Bottom 93.9(epoxy) 98.79(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	142.9	157.8	151.6	163.3	146.9

Date: May 20, 1991
Time: 22:04:20

Run ID No. 11X0XXX190

Voltage:	63.3 Volts	Fill Gas:	Air
Current:	2.53 Amps	Pressure:	0 psig
Power:	160.149 Watts		

Vessel Temperature: Box End - 47.7 deg C
TC End - 34.2 deg C

Heater Rod Temperature Distribution

154.5	166.4	172.8	175.1	174.6	173.0	165.3	153.4
162.6	178.0	186.4	189.6	190.1	185.9	176.5	160.6
164.0	---	190.5	194.9	195.0	189.5	180.8	163.7
162.4	179.9	189.4	193.9	192.7	189.1	180.1	163.3
161.0	176.8	185.4	188.5	188.5	184.9	176.4	159.5
155.8	169.0	176.7	180.5	180.5	176.9	169.2	155.7
148.8	160.5	166.3	168.1	168.1	165.2	159.9	149.5
139.9	145.1	149.3	150.8	150.6	149.1	144.3	139.8

Box Temperature Distribution

Top 107.7(epoxy) 112.5(under htr)

Right 107.3(epoxy) 110.5(under htr)

Left 105.8(epoxy) 110.5(under htr)

Bottom 102.1(epoxy) 107.4(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	153.2	169.7	164.5	176.9	159.7

Date: May 28, 1991
Time: 11:30:08

Run ID No. 11X0XXX200

Voltage:	77.0 Volts	Fill Gas:	Air
Current:	3.16 Amps	Pressure:	0 psig
Power:	243.32 Watts		

Vessel Temperature: Box End - 48.8 deg C
TC End - 38.7 deg C

Heater Rod Temperature Distribution

162.7	175.3	181.9	184.3	183.9	182.2	174.1	161.5
172.0	187.6	196.5	199.9	200.4	196.0	186.1	169.2
172.9	---	201.0	205.6	205.8	199.9	190.6	172.4
171.2	189.8	199.9	204.8	203.3	199.6	189.9	172.0
169.7	186.3	195.5	198.9	199.2	195.1	185.8	168.0
164.2	178.3	186.4	190.4	190.4	186.6	178.3	164.0
156.7	169.1	175.3	177.2	177.3	174.1	168.4	157.3
147.2	152.9	157.3	158.9	158.7	157.0	151.9	147.1

Box Temperature Distribution

Top 112.5(epoxy) 118.0(under htr)

Right 112.6(epoxy) 115.9(under htr)

Left 110.9(epoxy) 116.0(under htr)

Bottom 106.8(epoxy) 112.8(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	161.5	178.6	172.8	186.3	168.1

Date: June 8, 1991
Time: 12:15:08

Run ID No. 11X0XXX200

Voltage:	73.8 Volts	Fill Gas:	Air
Current:	2.85 Amps	Pressure:	0 psig
Power:	210.33 Watts		

Vessel Temperature: Box End - 49.6 deg C
TC End - 39.2 deg C

Heater Rod Temperature Distribution

162.5	175.1	181.7	184.1	183.7	182.0	173.9	161.4
171.5	187.4	196.3	199.7	200.2	195.8	186.0	169.2
172.9	---	200.8	205.2	205.6	199.7	190.4	172.4
171.3	189.7	199.9	204.8	203.3	199.5	189.9	172.1
169.8	186.3	195.5	198.9	199.2	195.1	185.9	168.1
164.4	178.4	186.6	190.6	190.6	186.8	178.6	164.2
157.0	169.3	175.6	177.5	177.6	174.4	168.7	157.6
147.7	153.3	157.7	159.3	159.1	157.4	152.3	147.4

Box Temperature Distribution

Top 113.1(epoxy) 118.7(under htr)

Right 113.1(epoxy) 116.6(under htr) Left 111.5(epoxy) 116.7(under htr)

Bottom 107.4(epoxy) 113.1(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	161.0	178.4	172.4	186.3	168.3

Date: May 28, 1991
Time: 21:11:42

Run ID No. 11X0XXX225

Voltage:	81.0 Volts	Fill Gas:	Air
Current:	3.28 Amps	Pressure:	0 psig
Power:	265.68 Watts		

Vessel Temperature: Box End - 54.7 deg C
TC End - 42.5 deg C

Heater Rod Temperature Distribution

182.5	196.3	203.6	206.5	205.8	204.0	195.0	181.3
193.0	210.5	220.2	224.0	224.6	219.7	208.9	190.3
194.8	---	225.9	230.9	231.2	224.7	214.4	194.2
193.3	214.1	225.5	230.7	229.2	225.0	214.3	194.2
192.1	210.8	221.3	225.0	225.2	220.7	210.2	190.1
186.2	202.3	211.6	216.1	216.1	211.7	202.3	185.9
177.9	192.2	199.5	201.7	201.8	198.0	191.4	178.6
167.3	174.0	179.2	181.1	180.9	178.9	172.9	167.1

Box Temperature Distribution

Top 128.2(epoxy) 134.5(under htr)

Right 128.3(epoxy) 132.3(under htr)

Left 126.4(epoxy) 132.3(under htr)

Bottom 121.6(epoxy) 128.5(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	180.7	199.9	194.9	209.8	190.6

Date: May 17, 1991
Time: 12:40:50

Run ID No. 11X0XXX240

Voltage:	86.0 Volts	Fill Gas:	Air
Current:	3.40 Amps	Pressure:	0 psig
Power:	292.4 Watts		

Vessel Temperature: Box End - 58.1 deg C
TC End - 40.8 deg C

Heater Rod Temperature Distribution

193.3	207.8	215.2	218.7	217.4	215.7	206.3	192.4
204.0	222.9	233.1	237.1	237.8	232.8	221.7	202.2
207.4	---	239.9	244.9	245.4	238.7	227.8	206.8
206.5	228.3	240.3	245.6	244.4	239.8	228.5	207.4
206.0	226.3	237.3	241.4	240.9	236.7	225.6	204.3
200.4	217.8	228.1	232.7	232.9	228.3	218.2	200.4
192.3	207.8	215.8	218.5	218.6	214.6	207.3	193.3
181.1	188.8	194.7	196.8	196.6	194.6	187.9	181.3

Box Temperature Distribution

Top 139.3(epoxy) 145.8(under htr)

Right 139.1(epoxy) 143.4(under htr)

Left 136.9(epoxy) 144.5(under htr)

Bottom 131.8(epoxy) 138.2(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	191.2	211.6	209.3	225.9	204.9

Date: May 21, 1991
Time: 11:17:51

Run ID No. 11X0XXX240

Voltage:	89.9 Volts	Fill Gas:	Air
Current:	3.52 Amps	Pressure:	0 psig
Power:	316.448 Watts		

Vessel Temperature: Box End - 56.2 deg C
TC End - 39.3 deg C

Heater Rod Temperature Distribution

193.4	207.9	215.6	218.8	217.8	216.0	206.7	192.3
204.1	223.2	233.5	237.5	238.0	232.9	221.6	201.9
207.0	---	239.9	245.3	245.5	238.6	227.8	206.6
205.8	227.9	239.9	245.4	244.0	239.6	228.2	206.9
204.9	225.0	236.1	240.0	240.0	235.6	224.5	202.9
198.7	216.1	226.3	231.1	231.0	226.5	216.3	198.7
190.2	205.8	213.6	216.1	216.2	212.4	205.0	191.0
179.0	186.2	192.1	194.2	194.0	191.9	185.3	178.8

Box Temperature Distribution

Top 137.1(epoxy) 144.0(under htr)

Right 136.9(epoxy) 141.6(under htr)

Left 134.8(epoxy) 141.6(under htr)

Bottom 129.8(epoxy) 136.9(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	191.5	211.8	208.0	223.8	203.6

Date: May 21, 1991
Time: 19:51:06

Run ID No. 11X0XXX250

Voltage:	96.1 Volts	Fill Gas:	Air
Current:	3.74 Amps	Pressure:	0 psig
Power:	359.414 Watts		

Vessel Temperature: Box End - 58.3 deg C
TC End - 40.3 deg C

Heater Rod Temperature Distribution

201.3	216.3	224.2	227.5	226.5	224.6	215.0	200.2
212.5	232.3	242.9	247.0	247.6	242.3	230.7	210.4
215.7	---	249.9	255.3	255.7	248.5	237.3	215.3
214.6	237.5	250.1	255.7	254.3	249.7	237.9	215.8
213.9	234.8	246.3	250.5	250.8	245.8	234.2	211.8
207.7	225.8	236.4	241.3	241.4	236.5	225.9	207.6
198.9	215.2	223.5	226.1	226.2	222.1	214.4	199.7
187.2	194.9	201.1	203.3	203.1	200.9	193.9	187.0

Box Temperature Distribution

Top 143.1(epoxy) 150.6(under htr)

Right 143.2(epoxy) 148.4(under htr) Left 141.0(epoxy) 148.2(under htr)

Bottom 135.7(epoxy) 143.4(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	199.3	220.2	216.9	233.1	212.7

Date: May 29, 1991
Time: 19:51:06

Run ID No. 11X0XXX250

Voltage:	100.5 Volts	Fill Gas:	Air
Current:	3.87 Amps	Pressure:	0 psig
Power:	388.935 Watts		

Vessel Temperature: Box End - 59.9 deg C
TC End - 45.3 deg C

Heater Rod Temperature Distribution

202.0	216.8	224.7	228.1	227.1	225.3	215.6	200.9
213.7	232.7	243.3	247.5	248.0	242.8	231.2	210.9
216.3	---	250.2	255.5	256.0	248.8	237.6	215.7
215.3	237.9	250.4	256.3	254.7	250.1	238.2	216.2
214.3	235.0	246.6	250.7	251.0	246.1	234.4	212.2
208.3	226.2	236.7	241.6	241.8	236.7	226.1	208.0
199.4	215.5	223.7	226.3	226.5	222.3	214.7	200.2
187.7	195.6	201.6	203.7	203.6	201.3	194.4	187.5

Box Temperature Distribution

Top 143.6(epoxy) 151.1(under htr)

Right 143.8(epoxy) 149.0(under htr)

Left 141.6(epoxy) 148.8(under htr)

Bottom 136.3(epoxy) 144.3(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	199.7	220.6	216.9	233.2	213.0

E.4 Above Atmospheric Pressure Nitrogen Test Data

This section of Appendix E contains the Test Data collected on the experimental apparatus above atmospheric pressure in nitrogen at 14 different Heater Rod power levels with the controlling temperature ranging from 70°C to 250°C without Boundary Condition Box side or end heaters operating. A Campaign Summary follows:

Vessel Pressure (psig)	Fill Gas	Box Temperature (deg C)	Central Heater Rod Temperature (deg C)	Run I.D. No.	Date Completed
15 psig	N_2	Not Controlled	70	21NPXXX070	6/9 7/6
			85	21NPXXX085	06/09/91
			100	21NPXXX100	06/10/91
			115	41NPXXX115	07/07/91
			125	21NPXXX125	06/11/91
			140	41NPXXX140	07/08/91
			150	21NPXXX150	06/11/91
			165	41NPXXX165	07/08/91
			175	21NPXXX175	06/11/91
			190	41NPXXX190	07/09/91
			200	21NPXXX200	06/12/91
			225	21NPXXX225	6/13 7/10
			240	41NPXXX240	07/09/91
			250	21NPXXX250	06/13/91

Date: June 9, 1991
Time: 12:52:26

Run ID No. 21NPXXX070

Voltage:	26.0 Volts	Fill Gas:	Nitrogen
Current:	1.00 Amps	Pressure:	17 psig
Power:	26.0 Watts		

Vessel Temperature: Box End - 31.0 deg C
TC End - 28.8 deg C

Heater Rod Temperature Distribution

66.2	69.71	71.56	72.34	72.59	72.23	70.08	66.29
68.4	72.39	74.16	75.06	75.25	74.23	72.0	67.73
67.44	---	73.33	74.16	74.27	73.12	71.37	67.24
65.74	69.55	71.21	72.49	71.7	71.2	69.53	65.71
64.2	67.34	68.8	69.33	69.45	68.79	67.29	63.7
62.08	64.44	65.57	66.25	66.19	65.72	64.66	62.04
59.77	61.58	62.36	62.41	62.43	61.9	61.39	59.82
57.31	57.38	57.52	57.71	57.68	57.5	57.12	57.1

Box Temperature Distribution

Top 47.1(epoxy) 48.27(under htr)

Right 46.9(epoxy) 47.46(under htr)

Left 46.6(epoxy) 47.64(under htr)

Bottom 45.2(epoxy) 46.53(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	65.8	69.91	61.67	66.6	60.82

Date: July 6, 1991
Time: 22:48:54

Run ID No. 41NPXXX070

Voltage:	22.2 Volts	Fill Gas:	Nitrogen
Current:	0.87 Amps	Pressure:	15 psig
Power:	19.314 Watts		

Vessel Temperature: Box End - 31.4 deg C
TC End - 29.1 deg C

Heater Rod Temperature Distribution

65.68	69.22	71.11	71.77	72.0	71.57	69.42	65.74
67.66	71.79	73.7	74.65	74.83	73.76	71.43	67.11
66.88	---	73.06	73.96	74.12	72.95	71.03	66.74
65.39	69.38	71.17	72.76	71.82	71.19	69.34	65.35
63.99	67.35	68.97	69.56	69.78	68.94	67.26	63.48
61.94	64.57	65.8	66.54	66.51	65.94	64.69	61.92
59.72	61.77	62.69	62.77	62.8	62.26	61.58	59.78
57.24	57.59	57.9	58.1	58.08	57.85	57.3	57.07

Box Temperature Distribution

Top 47.6(epoxy) 48.61(under htr)

Right 47.2(epoxy) 47.50(under htr)

Left 46.9(epoxy) 47.91(under htr)

Bottom 45.7(epoxy) 46.96(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	65.33	69.43	62.25	66.8	60.99

Date: June 9, 1991
Time: 22:13:34

Run ID No. 21NPXXX085

Voltage:	33.2 Volts	Fill Gas:	Nitrogen
Current:	1.28 Amps	Pressure:	16 psig
Power:	42.496 Watts		

Vessel Temperature: Box End - 33.2 deg C
TC End - 30.2 deg C

Heater Rod Temperature Distribution

78.61	83.34	85.71	86.22	86.5	86.48	83.56	78.41
81.92	87.15	89.47	90.56	90.82	89.56	86.63	80.97
80.84	---	88.6	89.69	89.84	88.37	86.06	80.63
78.75	83.79	85.98	87.71	86.61	85.96	83.75	78.73
76.77	80.95	82.89	83.59	83.76	82.87	80.89	76.1
74.03	77.19	78.71	79.59	79.54	78.89	77.45	74.01
71.06	73.47	74.52	74.62	74.63	73.95	73.27	71.18
67.86	68.02	68.21	68.46	68.44	68.2	67.71	67.67

Box Temperature Distribution

Top 54.6(epoxy) 56.12(under htr)

Right 54.2(epoxy) 55.01(under htr)

Left 53.7(epoxy) 55.23(under htr)

Bottom 52.0(epoxy) 53.64(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	77.81	83.84	73.24	79.8	72.42

Date: June 10, 1991
Time: 14:22:34

Run ID No. 21NPXXX100

Voltage:	38.0 Volts	Fill Gas:	Nitrogen
Current:	1.47 Amps	Pressure:	15 psig
Power:	55.86 Watts		

Vessel Temperature: Box End - 35.3 deg C
TC End - 31.7 deg C

Heater Rod Temperature Distribution

91.44	97.25	100.4	101.5	101.8	101.2	97.7	91.76
95.1	101.8	104.9	106.4	106.7	105.1	101.3	94.16
93.88	---	104.1	105.5	105.7	103.7	100.6	93.66
91.39	97.94	100.9	102.9	101.8	100.9	97.97	91.45
89.02	94.52	97.17	98.12	98.33	97.12	94.46	88.25
85.66	89.9	91.97	93.18	93.1	92.23	90.19	85.64
81.98	85.27	86.73	86.91	86.97	86.1	85.02	82.16
78.05	78.52	78.92	79.27	79.22	78.88	78.03	77.75

Box Temperature Distribution

Top 61.9(epoxy) 63.86(under htr)

Right 61.6(epoxy) 62.53(under htr)

Left 60.9(epoxy) 62.98(under htr)

Bottom 58.8(epoxy) 60.93(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	90.74	97.81	85.39	93.4	84.14

Date: July 7, 1991
Time: 21:17:46

Run ID No. 41NPXXX115

Voltage:	40.4 Volts	Fill Gas:	Nitrogen
Current:	1.58 Amps	Pressure:	13 psig
Power:	63.832 Watts		

Vessel Temperature: Box End - 36.8 deg C
TC End - 32.2 deg C

Heater Rod Temperature Distribution

102.9	109.9	113.6	114.9	115.3	114.5	110.2	103.1
107.3	115.5	119.4	121.1	121.5	119.5	114.8	106.2
106.1	---	118.7	120.5	120.9	118.4	114.5	105.9
103.5	111.6	115.4	117.8	116.6	115.4	111.6	103.5
100.8	107.7	111.1	112.3	112.5	111.0	107.6	99.88
96.92	102.3	105.0	106.5	106.4	105.2	102.5	96.87
92.54	96.78	98.75	99.01	99.07	97.98	96.53	92.78
87.83	88.54	89.27	89.73	89.67	89.17	88.06	87.46

Box Temperature Distribution

Top 68.4(epoxy) 70.80(under htr)

Right 68.1(epoxy) 69.23(under htr)

Left 67.4(epoxy) 69.75(under htr)

Bottom 64.9(epoxy) 67.44(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	102.0	110.6	97.02	106.3	95.19

Date: June 11, 1991
Time: 00:04:14

Run ID No. 21NPXXX125

Voltage:	51.4 Volts	Fill Gas:	Nitrogen
Current:	1.99 Amps	Pressure:	16 psig
Power:	102.286 Watts		

Vessel Temperature: Box End - 38.7 deg C
TC End - 33.7 deg C

Heater Rod Temperature Distribution

111.9	119.6	123.3	123.7	124.0	124.3	119.7	111.5
117.6	126.1	129.9	131.5	131.9	130.1	125.3	116.1
116.2	---	129.1	130.8	131.1	128.6	124.8	115.9
113.0	121.4	125.2	127.5	126.2	125.2	121.5	113.2
110.0	117.0	120.3	121.5	121.5	120.2	116.9	108.9
105.7	111.0	113.7	115.1	115.0	113.9	111.3	105.6
100.9	105.0	106.8	107.0	107.1	105.9	104.7	101.2
95.81	96.27	96.63	97.06	97.05	96.59	95.69	95.61

Box Temperature Distribution

Top 73.9(epoxy) 76.74(under htr)

Right 73.4(epoxy) 74.77(under htr) Left 72.7(epoxy) 75.05(under htr)

Bottom 69.8(epoxy) 72.46(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	110.7	120.6	103.2	114.9	103.2

Date: July 8, 1991
Time: 11:11:03

Run ID No. 41NPXXX140

Voltage:	51.8 Volts	Fill Gas:	Nitrogen
Current:	2.01 Amps	Pressure:	15 psig
Power:	104.118 Watts		

Vessel Temperature: Box End - 40.6 deg C
TC End - 34.8 deg C

Heater Rod Temperature Distribution

123.8	132.5	137.0	137.9	138.2	138.0	132.7	123.7
130.4	140.1	144.7	146.6	147.1	144.9	139.2	128.5
128.9	---	144.2	146.3	146.7	143.7	139.1	128.5
125.6	135.6	140.2	143.0	141.6	140.2	135.6	125.8
122.4	130.8	134.9	136.3	136.4	134.8	130.7	121.2
117.6	124.1	127.4	129.2	129.0	127.6	124.4	117.5
112.1	117.2	119.5	119.9	119.9	118.6	116.9	112.4
106.2	107.0	107.7	108.2	108.2	107.6	106.3	105.9

Box Temperature Distribution

Top 81.0(epoxy) 84.36(under htr)

Right 80.6(epoxy) 82.19(under htr)

Left 79.6(epoxy) 82.44(under htr)

Bottom 76.5(epoxy) 79.77(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	122.7	133.8	115.1	128.7	114.8

Date: June 11, 1991
Time: 12:35:18

Run ID No. 21NPXXX150

Voltage:	64.9 Volts	Fill Gas:	Nitrogen
Current:	2.53 Amps	Pressure:	15 psig
Power:	164.197 Watts		

Vessel Temperature: Box End - 42.7 deg C
TC End - 36.4 deg C

Heater Rod Temperature Distribution

132.1	141.4	146.2	147.0	147.4	147.2	141.5	131.9
138.9	149.5	154.5	156.5	157.0	154.7	148.6	137.2
137.7	---	154.1	156.4	156.8	153.5	148.6	137.4
134.1	145.0	150.0	152.9	151.4	149.9	145.1	134.5
130.9	140.0	144.4	145.9	146.0	144.3	139.9	129.6
125.7	132.8	136.5	138.4	138.3	136.7	133.2	125.7
119.9	125.5	128.0	128.5	128.5	127.0	125.2	120.3
113.6	114.6	115.4	116.0	116.0	115.4	113.9	113.3

Box Temperature Distribution

Top 86.6(epoxy) 90.25(under htr)

Right 86.0(epoxy) 87.86(under htr) Left 85.0(epoxy) 87.97(under htr)

Bottom 81.6(epoxy) 84.97(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	130.8	142.9	123.0	137.8	123.3

Date: July 8, 1991
Time: 21:35:04

Run ID No. 41NPXXX165

Voltage:	65.2 Volts	Fill Gas:	Nitrogen
Current:	2.53 Amps	Pressure:	16 psig
Power:	164.956 Watts		

Vessel Temperature: Box End - 46.1 deg C
TC End - 38.8 deg C

Heater Rod Temperature Distribution

145.4	155.6	160.9	161.3	161.5	161.8	155.4	144.7
153.3	164.9	170.4	172.6	173.2	170.6	163.8	151.2
151.9	---	170.3	172.9	173.3	169.7	164.1	151.5
148.2	160.3	165.9	169.4	167.6	165.9	160.5	148.6
144.8	154.9	160.0	161.7	161.9	159.8	154.9	143.4
139.2	147.2	151.2	153.5	153.2	151.5	147.4	139.1
132.8	139.2	142.0	142.5	142.6	140.9	138.8	133.3
126.0	127.0	128.0	128.6	128.6	127.8	126.2	125.6

Box Temperature Distribution

Top 95.2(epoxy) 99.52(under htr)

Right 94.6(epoxy) 96.87(under htr) Left 93.5(epoxy) 97.02(under htr)

Bottom 89.8(epoxy) 93.80(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	143.6	157.2	134.9	152.2	135.9

Date: June 11, 1991
Time: 23:33:19

Run ID No. 21NPXXX175

Voltage:	74.8 Volts	Fill Gas:	Nitrogen
Current:	2.89 Amps	Pressure:	15 psig
Power:	216.172 Watts		

Vessel Temperature: Box End - 46.5 deg C
TC End - 38.7 deg C

Heater Rod Temperature Distribution

153.2	164.0	169.9	171.8	172.3	171.2	164.5	153.7
161.0	173.6	179.8	182.5	183.1	180.2	172.7	159.2
159.7	---	179.8	182.7	183.2	179.2	173.1	159.5
155.8	169.0	175.3	178.9	177.1	175.2	169.3	156.4
152.3	163.4	169.0	170.8	171.0	168.8	163.4	150.9
146.4	155.1	159.6	162.0	161.9	159.9	155.4	146.4
139.6	146.6	149.8	150.3	150.5	148.6	146.2	140.1
132.2	133.6	134.7	135.5	135.5	134.6	132.6	131.8

Box Temperature Distribution

Top 99.3(epoxy) 104.1(under htr)

Right 98.8(epoxy) 101.2(under htr)

Left 97.6(epoxy) 101.3(under htr)

Bottom 93.5(epoxy) 97.71(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	151.5	165.6	142.3	160.8	143.7

Date: July 9, 1991
Time: 11:39:13

Run ID No. 41NPXXX190

Voltage:	77.4 Volts	Fill Gas:	Nitrogen
Current:	3.0 Amps	Pressure:	15 psig
Power:	232.2 Watts		

Vessel Temperature: Box End - 48.9 deg C
TC End - 40.0 deg C

Heater Rod Temperature Distribution

164.8	176.7	183.2	185.2	185.7	184.5	177.0	165.1
173.3	187.5	194.7	197.7	198.3	195.1	186.6	171.4
172.4	---	195.4	198.7	199.3	194.7	187.6	172.1
168.5	183.6	191.0	195.0	193.3	191.0	183.9	169.2
165.0	177.7	184.4	186.6	186.7	184.2	177.8	163.3
158.6	168.8	174.2	177.1	176.9	174.5	169.1	158.5
151.1	159.4	163.3	164.1	164.2	162.0	159.0	151.7
143.0	145.0	146.7	147.6	147.6	146.5	144.0	142.6

Box Temperature Distribution

Top 107.4(epoxy) 112.7(under htr)

Right 106.8(epoxy) 109.7(under htr)

Left 105.5(epoxy) 109.8(under htr)

Bottom 101.0(epoxy) 105.7(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	162.8	178.4	155.2	174.8	156.1

Date: June 12, 1991
Time: 13:47:25

Run ID No. 21NPXXX200

Voltage:	84.0 Volts	Fill Gas:	Nitrogen
Current:	3.24 Amps	Pressure:	15 psig
Power:	272.16 Watts		

Vessel Temperature: Box End - 50.6 deg C
TC End - 41.1 deg C

Heater Rod Temperature Distribution

172.0	184.6	191.3	193.4	193.9	192.5	184.6	172.1
180.8	196.0	203.6	206.8	207.5	203.9	194.9	178.9
180.2	---	204.8	208.3	208.8	203.8	196.2	179.8
176.1	192.3	200.2	204.5	202.7	200.2	192.6	176.9
172.6	186.3	193.5	195.9	196.0	193.2	186.2	170.9
166.0	177.0	182.9	186.0	185.9	183.2	177.3	165.9
158.2	167.3	171.5	172.4	172.5	170.2	166.8	158.9
149.7	152.1	154.0	155.0	155.1	153.9	151.0	149.4

Box Temperature Distribution

Top 112.8(epoxy) 118.4(under htr)

Right 112.1(epoxy) 115.3(under htr) Left 110.8(epoxy) 115.4(under htr)

Bottom 106.0(epoxy) 111.1(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	169.9	186.3	162.9	183.4	164.2

Date: June 13, 1991
Time: 00:34:34

Run ID No. 21NPXXX225

Voltage:	99.1 Volts	Fill Gas:	Nitrogen
Current:	3.84 Amps	Pressure:	15 psig
Power:	380.544 Watts		

Vessel Temperature: Box End - 53.5 deg C
TC End - 42.3 deg C

Heater Rod Temperature Distribution

192.0	206.3	213.9	216.3	216.8	215.3	206.3	192.3
202.4	219.6	228.3	231.8	232.6	228.7	218.4	200.2
202.0	---	230.1	234.2	234.8	229.1	220.5	201.7
197.8	216.4	225.6	230.2	228.5	225.5	216.7	198.8
194.1	209.9	218.2	221.0	221.1	217.9	209.9	192.1
186.6	199.5	206.5	210.0	209.9	206.7	199.9	186.6
177.7	188.4	193.4	194.5	194.6	191.8	187.8	178.5
168.0	170.8	173.2	174.4	174.4	173.0	169.6	167.6

Box Temperature Distribution

Top 125.2(epoxy) 131.9(under htr)

Right 124.6(epoxy) 128.3(under htr)

Left 123.1(epoxy) 128.4(under htr)

Bottom 117.4(epoxy) 123.4(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	189.2	208.0	181.0	205.7	184.2

Date: July 10, 1991
Time: 10:35:30

Run ID No. 21NPXXX225

Voltage:	89.0 Volts	Fill Gas:	Nitrogen
Current:	3.43 Amps	Pressure:	15 psig
Power:	305.27 Watts		

Vessel Temperature: Box End - 54.7 deg C
TC End - 43.5 deg C

Heater Rod Temperature Distribution

191.6	205.8	213.4	215.7	216.3	214.8	205.8	191.8
202.0	219.1	227.8	231.3	232.1	228.2	217.9	199.8
201.6	---	229.7	233.8	234.5	228.9	220.1	201.3
197.6	216.2	225.5	230.5	228.5	225.5	216.6	198.5
194.0	209.9	218.3	221.2	221.5	218.0	209.9	192.0
186.6	199.6	206.7	210.3	210.1	206.9	199.9	186.5
177.7	188.5	193.6	194.7	195.0	192.2	188.1	178.6
168.3	171.1	173.7	174.9	174.9	173.5	170.0	167.8

Box Temperature Distribution

Top 125.8(epoxy) 132.7(under htr)

Right 125.3(epoxy) 129.2(under htr) Left 123.8(epoxy) 129.2(under htr)

Bottom 118.2(epoxy) 123.5(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	188.6	207.5	181.8	206.0	184.2

Date: July 9, 1991
Time: 23:22:04

Run ID No. 41NPXXX240

Voltage:	96.1 Volts	Fill Gas:	Nitrogen
Current:	3.70 Amps	Pressure:	16 psig
Power:	355.57 Watts		

Vessel Temperature: Box End - 57.9 deg C
TC End - 45.5 deg C

Heater Rod Temperature Distribution

203.8	218.8	226.9	229.3	229.9	228.2	218.7	203.9
214.9	233.1	242.3	246.1	246.9	242.7	231.9	212.6
214.8	---	244.8	249.3	249.9	243.8	234.5	214.5
210.8	230.7	240.6	245.8	243.9	240.7	231.2	211.7
207.2	224.2	233.3	236.4	236.7	233.0	224.3	205.0
199.4	213.5	221.2	225.1	224.9	221.3	213.8	199.3
190.0	201.7	207.4	208.6	208.9	205.9	201.3	191.0
179.8	183.1	186.0	187.3	187.4	185.8	181.8	179.4

Box Temperature Distribution

Top 134.7(epoxy) 142.0(under htr)

Right 134.1(epoxy) 138.2(under htr)   Left 132.3(epoxy) 138.4(under htr)

Bottom 126.4(epoxy) 132.7(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	200.7	220.4	193.5	219.7	196.9

Date: June 13, 1991
Time: 15:34:43

Run ID No. 21NPXXX250

Voltage:	100.7 Volts	Fill Gas:	Nitrogen
Current:	3.87 Amps	Pressure:	14 psig
Power:	389.709 Watts		

Vessel Temperature: Box End - 58.8 deg C
TC End - 45.7 deg C

Heater Rod Temperature Distribution

210.1	226.0	234.4	236.8	237.2	235.4	225.5	210.1
221.8	241.0	251.0	255.0	255.8	251.3	239.7	219.3
222.2	---	254.3	259.1	259.8	253.2	243.1	221.7
218.4	239.7	250.6	256.0	254.2	250.6	240.1	219.4
214.9	233.5	243.4	246.8	247.0	243.1	233.5	212.8
207.1	222.5	231.1	235.3	235.3	231.3	222.8	207.0
197.3	210.4	216.7	218.3	218.5	215.2	209.9	198.3
186.3	190.5	194.2	195.7	195.8	194.0	189.3	186.0

Box Temperature Distribution

Top 139.7(epoxy) 147.4(under htr)

Right 139.2(epoxy) 143.8(under htr)

Left 137.3(epoxy) 143.7(under htr)

Bottom 131.3(epoxy) 138.4(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	206.9	227.7	203.0	228.9	205.9

E.5 Above Atmospheric Pressure Argon Test Data

This section of Appendix E contains the Test Data collected on the experimental apparatus above atmospheric pressure (15 psig) in argon at 14 different Heater Rod power levels with the controlling temperature ranging from 70°C to 250°C without Boundary Condition Box side or end heaters operating. A Campaign Summary follows:

Vessel Pressure (psig)	Fill Gas	Box Temperature (deg C)	Central Heater Rod Temperature (deg C)	Run I.D. No.	Date Completed
15 psig	Ar	Not Controlled	70	21APXXX070	7/10 7/14
			85	21APXXX085	07/11/91
			100	21APXXX100	07/11/91
			115	41APXXX115	07/15/91
			125	21APXXX125	7/12 7/12
			140	41APXXX140	07/15/91
			150	21APXXX150	07/12/91
			165	41APXXX165	07/16/91
			175	21APXXX175	07/12/91
			190	41APXXX190	07/16/91
			200	21APXXX200	07/13/91
			225	21APXXX225	07/13/91
			240	41APXXX240	07/17/91
			250	21APXXX250	07/14/91

Date: July 10, 1991
Time: 21:14:26

Run ID No. 21APXXX070

Voltage:	18.6 Volts	Fill Gas:	Argon
Current:	0.72 Amps.	Pressure:	15 psig
Power:	13.392 Watts		

Vessel Temperature: Box End - 32.7 deg C
TC End - 30.0 deg C

Heater Rod Temperature Distribution

65.45	68.81	70.57	71.1	71.29	70.9	68.75	65.25
67.43	71.55	73.47	74.36	74.52	73.49	71.15	66.87
67.01	---	73.3	74.15	74.34	73.01	71.07	66.76
65.78	69.79	71.7	72.89	72.24	71.67	69.75	65.7
64.53	67.97	69.65	70.29	70.34	69.6	67.85	64.04
62.69	65.43	66.77	67.54	67.47	66.86	65.53	62.67
60.69	62.83	63.83	63.96	63.93	63.35	62.57	60.68
58.4	58.9	59.25	59.48	59.44	59.22	58.63	58.25

Box Temperature Distribution

Top 48.9(epoxy) 50.32(under htr)

Right 49.1(epoxy) 49.17(under htr)

Left 48.8(epoxy) 49.74(under htr)

Bottom 47.2(epoxy) 48.63(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	65.05	69.33	62.54	67.6	62.37

Date: July 14, 1991
Time: 20:33:55

Run ID No. 41APXXX070

Voltage:	19.1 Volts	Fill Gas:	Argon
Current:	0.74 Amps	Pressure:	15 psig
Power:	14.134 Watts		

Vessel Temperature: Box End - 31.9 deg C
TC End - 29.4 deg C

Heater Rod Temperature Distribution

65.48	68.96	70.77	71.34	71.55	71.17	68.97	65.33
67.54	71.79	73.79	74.7	74.89	73.83	71.42	67.0
67.11	---	73.55	74.46	74.62	73.3	71.33	66.87
65.8	69.96	71.88	73.17	72.45	71.84	69.9	65.75
64.53	68.05	69.74	70.39	70.43	69.7	67.92	64.02
62.59	65.39	66.73	67.48	67.45	66.84	65.48	62.6
60.54	62.69	63.68	63.8	63.8	63.2	62.43	60.53
58.13	58.64	58.97	59.19	59.14	58.91	58.35	58.0

Box Temperature Distribution

Top 48.3(epoxy) 49.76(under htr)

Right 48.5(epoxy) 48.55(under htr)

Left 48.2(epoxy) 49.13(under htr)

Bottom 46.6(epoxy) 47.86(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	65.09	69.52	62.39	67.6	62.09

Date: July 11, 1991
Time: 11:18:52

Run ID No. 21APXXX085

Voltage:	26.0 Volts	Fill Gas:	Argon
Current:	1.03 Amps	Pressure:	15 psig
Power:	26.78 Watts		

Vessel Temperature: Box End - 33.8 deg C
TC End - 30.4 deg C

Heater Rod Temperature Distribution

77.93	82.55	84.92	85.47	85.68	85.45	82.54	77.68
81.15	86.5	89.05	90.18	90.43	89.11	86.01	80.22
80.47	---	88.8	89.97	90.2	88.62	86.11	80.29
78.99	84.32	86.8	88.73	87.73	86.78	84.28	78.82
77.33	81.92	84.13	84.98	85.16	84.09	81.82	76.68
74.83	78.44	80.22	81.17	81.13	80.33	78.59	74.82
72.08	74.88	76.17	76.33	76.36	75.59	74.65	72.15
69.05	69.53	69.9	70.2	70.15	69.86	69.23	68.84

Box Temperature Distribution

Top 55.2(epoxy) 57.17(under htr)

Right 55.4(epoxy) 56.11(under htr)

Left 55.1(epoxy) 56.40(under htr)

Bottom 53.0(epoxy) 54.81(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	77.34	83.48	73.66	81.2	73.83

Date: July 11, 1991
Time: 19:21:55

Run ID No. 21APXXX100

Voltage:	31.3 Volts	Fill Gas:	Argon
Current:	1.20 Amps	Pressure:	16 psig
Power:	37.56 Watts		

Vessel Temperature: Box End - 36.0 deg C
TC End - 31.8 deg C

Heater Rod Temperature Distribution

90.42	96.25	99.09	99.28	99.46	99.73	96.15	90.0
94.87	101.5	104.4	105.7	106.0	104.5	100.8	93.71
94.12	---	104.2	105.6	105.9	103.9	101.0	93.86
92.23	98.75	101.7	103.4	102.6	101.7	98.77	92.08
90.08	95.66	98.31	99.3	99.17	98.25	95.55	89.28
86.97	91.34	93.47	94.6	94.52	93.61	91.53	86.94
83.55	86.89	88.37	88.58	88.5	87.52	86.48	83.54
79.74	80.21	80.51	80.88	80.82	80.46	79.85	79.49

Box Temperature Distribution

Top 62.7(epoxy) 64.97(under htr)

Right 62.9(epoxy) 63.61(under htr)

Left 62.3(epoxy) 64.23(under htr)

Bottom 59.7(epoxy) 61.95(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	89.72	97.58	84.5	93.9	85.52

Date: July 15, 1991
Time: 09:14:04

Run ID No. 41APXXX115

Voltage:	35.4 Volts	Fill Gas:	Argon
Current:	1.40 Amps	Pressure:	15 psig
Power:	49.56 Watts		

Vessel Temperature: Box End - 37.5 deg C
TC End - 32.5 deg C

Heater Rod Temperature Distribution

101.0	107.9	111.3	111.5	111.7	111.9	107.6	100.5
106.0	114.0	117.7	119.3	119.7	117.9	113.3	104.8
105.4	---	117.8	119.6	119.9	117.4	113.7	105.1
103.2	111.1	114.9	117.4	116.1	114.9	111.2	103.2
100.9	107.7	111.0	112.3	112.5	110.9	107.5	100.0
97.28	102.7	105.3	106.7	106.7	105.5	102.9	97.29
93.34	97.5	99.39	99.7	99.79	98.61	97.21	93.55
89.08	89.89	90.48	90.94	90.83	90.31	89.45	88.83

Box Temperature Distribution

Top 69.7(epoxy) 72.38(under htr)

Right 69.8(epoxy) 70.90(under htr)

Left 69.2(epoxy) 71.40(under htr)

Bottom 66.2(epoxy) 68.72(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	100.2	109.5	95.34	106.7	95.97

Date: July 12, 1991
Time: 08:30:29

Run ID No. 21APXXX125

Voltage:	37.3 Volts	Fill Gas:	Argon
Current:	1.42 Amps	Pressure:	15 psig
Power:	52.966 Watts		

Vessel Temperature: Box End - 39.4 deg C
TC End - 33.7 deg C

Heater Rod Temperature Distribution

109.1	116.6	120.3	120.6	120.7	120.9	116.2	108.6
114.6	123.3	127.3	129.0	129.4	127.5	122.5	113.3
114.0	---	127.6	129.4	129.8	126.9	122.8	113.5
111.5	120.2	124.3	126.8	125.5	124.3	120.3	111.5
108.9	116.4	120.0	121.4	121.7	119.9	116.2	107.9
105.1	110.9	113.9	115.5	115.4	114.1	111.1	104.9
100.7	105.3	107.4	107.8	107.9	106.6	105.0	100.9
96.13	97.03	97.74	98.24	98.17	97.66	96.59	95.86

Box Temperature Distribution

Top 74.9(epoxy) 78.09(under htr)

Right 75.2(epoxy) 76.35(under htr) Left 74.5(epoxy) 76.48(under htr)

Bottom 71.1(epoxy) 74.09(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	108.1	118.2	102.7	115.5	103.9

Date: July 12, 1991
Time: 08:49:28

Run ID No. 21APXXX125

Voltage:	38.8 Volts	Fill Gas:	Argon
Current:	1.52 Amps	Pressure:	15 psig
Power:	58.976 Watts		

Vessel Temperature: Box End - 39.3 deg C
TC End - 33.6 deg C

Heater Rod Temperature Distribution

109.7	117.2	120.9	121.2	121.3	121.5	116.9	109.2
115.4	124.0	128.0	129.6	130.0	128.1	123.2	114.0
114.7	---	128.2	130.2	130.5	127.9	123.9	114.6
112.6	121.4	125.5	128.4	127.0	125.5	121.5	112.5
110.3	117.9	121.7	123.0	123.3	121.5	117.8	109.3
106.4	112.5	115.6	117.1	117.0	115.7	112.7	106.4
102.1	106.9	109.0	109.4	109.5	108.2	106.6	102.4
97.35	98.35	99.03	99.56	99.52	98.97	97.86	97.09

Box Temperature Distribution

Top 75.0(epoxy) 78.06(under htr)

Right 75.2(epoxy) 76.30(under htr)

Left 74.5(epoxy) 76.45(under htr)

Bottom 71.1(epoxy) 74.06(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	108.9	119.1	103.2	116.7	104.9

Date: July 15, 1991
Time: 20:15:48

Run ID No. 41APXXX140

Voltage:	44.2 Volts	Fill Gas:	Argon
Current:	1.74 Amps	Pressure:	15 psig
Power:	76.908 Watts		

Vessel Temperature: Box End - 41.9 deg C
TC End - 35.3 deg C

Heater Rod Temperature Distribution

122.1	130.5	134.8	135.1	135.3	135.5	130.2	121.5
128.7	138.4	143.1	144.9	145.4	143.3	137.6	127.0
128.0	---	143.5	145.7	146.2	143.2	138.5	127.7
125.5	135.7	140.5	143.6	142.2	140.6	135.9	125.7
123.0	131.7	136.1	137.6	137.9	136.0	131.6	121.9
118.6	125.6	129.2	130.9	130.9	129.3	125.8	118.6
113.7	119.2	121.7	122.2	122.3	120.7	118.8	114.0
108.2	109.4	110.3	110.9	110.8	110.1	108.9	108.0

Box Temperature Distribution

Top 82.9(epoxy) 86.56(under htr)

Right 83.3(epoxy) 84.62(under htr)

Left 82.3(epoxy) 84.86(under htr)

Bottom 78.4(epoxy) 81.67(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	121.1	132.7	114.9	130.3	116.8

Date: July 12, 1991
Time: 16:08:55

Run ID No. 21APXXX150

Voltage:	46.7 Volts	Fill Gas:	Argon
Current:	1.82 Amps	Pressure:	16 psig
Power:	84.994 Watts		

Vessel Temperature: Box End - 43.7 deg C
TC End - 36.5 deg C

Heater Rod Temperature Distribution

130.6	139.8	144.4	144.7	144.9	145.2	139.5	130.1
137.7	148.3	153.2	155.2	155.8	153.5	147.4	136.1
137.2	---	153.9	156.4	156.7	153.4	148.4	136.8
134.6	145.5	150.6	153.7	152.3	150.7	145.6	134.5
131.7	141.2	145.9	147.5	147.7	145.7	141.1	130.5
127.1	134.6	138.5	140.4	140.3	138.6	134.8	127.0
121.7	127.6	130.4	130.9	130.9	129.3	127.2	122.0
115.9	117.1	118.0	118.7	118.7	117.9	116.5	115.6

Box Temperature Distribution

Top 88.2(epoxy) 92.42(under htr)

Right 88.7(epoxy) 90.18(under htr)

Left 87.7(epoxy) 90.35(under htr)

Bottom 83.4(epoxy) 86.98(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	129.4	142.1	122.4	139.5	125.2

Date: July 16, 1991
Time: 09:27:47

Run ID No. 41APXXX165

Voltage:	51.3 Volts	Fill Gas:	Argon
Current:	2.01 Amps	Pressure:	14 psig
Power:	103.113 Watts		

Vessel Temperature: Box End - 45.4 deg C
TC End - 36.9 deg C

Heater Rod Temperature Distribution

142.2	152.0	157.1	158.7	159.0	158.0	151.8	142.0
149.4	161.2	167.2	169.7	170.3	167.5	160.4	147.8
149.1	---	168.4	171.2	171.7	167.8	161.9	148.8
146.3	159.0	165.2	168.8	167.2	165.2	159.2	146.7
143.7	154.6	160.2	162.2	162.4	160.0	154.4	142.4
138.6	147.5	152.2	154.5	154.4	152.3	147.7	138.6
132.7	140.0	143.3	144.0	144.1	142.1	139.4	133.0
126.1	128.0	129.5	130.3	130.2	129.2	127.3	125.8

Box Temperature Distribution

Top 95.6(epoxy) 100.5(under htr)

Right 96.3(epoxy) 98.24(under htr)

Left 95.1(epoxy) 98.37(under htr)

Bottom 90.4(epoxy) 94.45(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	140.9	154.4	134.9	153.1	137.5

Date: July 12, 1991
Time: 23:44:03

Run ID No. 21APXXX175

Voltage:	55.7 Volts	Fill Gas:	Argon
Current:	2.16 Amps	Pressure:	16 psig
Power:	120.312 Watts		

Vessel Temperature: Box End - 47.5 deg C
TC End - 38.3 deg C

Heater Rod Temperature Distribution

151.2	161.6	167.1	168.7	169.2	168.1	161.5	151.1
159.1	171.6	177.8	180.5	181.1	178.2	170.7	157.3
158.7	---	179.2	182.2	182.7	178.5	172.3	158.4
155.9	169.2	175.8	179.4	177.8	175.8	169.5	156.1
153.0	164.5	170.4	172.4	172.6	170.2	164.4	151.6
147.7	156.9	161.9	164.3	164.2	162.0	157.2	147.6
141.4	148.9	152.4	153.1	153.2	151.1	148.4	141.7
134.4	136.3	137.7	138.6	138.5	137.6	135.5	134.0

Box Temperature Distribution

Top 101.4(epoxy) 106.7(under htr)

Right 102.0(epoxy) 104.1(under htr)

Left 100.8(epoxy) 104.1(under htr)

Bottom 95.7(epoxy) 100.0(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	149.8	164.2	142.1	162.4	146.1

Date: July 16, 1991
Time: 18:09:45

Run ID No. 41APXXX190

Voltage:	62.8 Volts	Fill Gas:	Argon
Current:	2.46 Amps	Pressure:	16 psig
Power:	154.488 Watts		

Vessel Temperature: Box End - 50.0 deg C
TC End - 39.7 deg C

Heater Rod Temperature Distribution

162.4	173.8	179.8	181.5	182.0	180.8	173.6	162.3
171.2	184.9	191.9	194.7	195.4	192.2	183.9	169.2
171.0	---	193.8	197.2	197.7	193.0	186.1	170.7
168.0	183.0	190.5	194.7	192.8	190.4	183.3	168.6
165.3	178.2	184.9	187.2	187.6	184.6	178.0	163.7
159.5	170.0	175.7	178.4	178.3	175.8	170.3	159.5
152.7	161.3	165.4	166.2	166.4	164.1	160.9	153.3
145.3	147.7	149.5	150.5	150.4	149.2	146.8	145.0

Box Temperature Distribution

Top 109.1(epoxy) 115.2(under htr)

Right 109.9(epoxy) 112.6(under htr) Left 108.5(epoxy) 112.6(under htr)

Bottom 103.1(epoxy) 107.9(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	160.8	176.5	153.9	175.8	158.2

Date: July 13, 1991
Time: 11:45:07

Run ID No. 21APXXX200

Voltage:	65.9 Volts	Fill Gas:	Argon
Current:	2.56 Amps	Pressure:	15 psig
Power:	168.704 Watts		

Vessel Temperature: Box End - 52.1 deg C
TC End - 40.9 deg C

Heater Rod Temperature Distribution

170.3	182.2	188.5	190.3	190.7	189.4	181.8	169.9
179.5	194.0	201.5	204.6	205.3	201.8	193.0	177.4
179.5	---	203.9	207.6	208.1	203.2	195.7	179.2
176.7	192.7	200.9	205.3	203.5	200.9	193.1	177.2
174.0	187.9	195.4	197.9	198.2	195.0	187.8	172.3
168.0	179.5	185.8	188.8	188.7	185.8	179.7	168.0
160.9	170.3	174.9	175.9	176.1	173.5	169.9	161.4
152.8	155.8	158.0	159.1	159.1	157.8	154.8	152.6

Box Temperature Distribution

Top 115.1(epoxy) 121.8(under htr)

Right 116.2(epoxy) 118.9(under htr)

Left 114.6(epoxy) 118.8(under htr)

Bottom 108.9(epoxy) 114.0(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	168.3	185.1	162.4	185.6	167.4

Date: July 13, 1991
Time: 20:54:04

Run ID No. 21APXXX225

Voltage:	76.6 Volts	Fill Gas:	Argon
Current:	2.97 Amps	Pressure:	16 psig
Power:	227.502 Watts		

Vessel Temperature: Box End - 56.7 deg C
TC End - 43.4 deg C

Heater Rod Temperature Distribution

189.9	203.3	210.3	212.4	212.8	211.3	202.8	189.6
200.4	216.9	225.4	228.9	229.6	225.8	215.8	198.2
201.1	---	228.9	233.0	233.6	227.9	219.3	200.6
198.1	216.6	226.0	230.9	229.1	225.9	217.1	198.8
195.5	211.6	220.2	223.2	223.5	219.9	211.5	193.6
188.9	202.4	209.8	213.4	213.2	209.8	202.6	188.8
180.9	192.1	197.6	198.9	199.1	196.1	191.6	181.5
171.8	175.5	178.3	179.7	179.7	178.1	174.5	171.5

Box Temperature Distribution

Top 129.1(epoxy) 137.1(under htr)

Right 130.4(epoxy) 133.8(under htr) Left 128.6(epoxy) 133.7(under htr)

Bottom 121.9(epoxy) 128.1(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	187.3	206.3	182.0	208.3	188.4

Date: July 17, 1991
Time: 10:04:17

Run ID No. 41APXXX240

Voltage:	83.5 Volts	Fill Gas:	Argon
Current:	3.23 Amps	Pressure:	15 psig
Power:	269.705 Watts		

Vessel Temperature: Box End - 59.4 deg C
TC End - 44.5 deg C

Heater Rod Temperature Distribution

200.9	215.0	222.4	224.5	224.8	223.2	214.1	200.3
211.9	229.5	238.7	242.3	243.1	238.9	228.3	209.7
213.1	---	243.0	247.5	248.1	241.8	232.5	212.6
210.4	230.4	240.7	245.7	243.9	240.6	230.8	211.2
207.9	225.4	235.0	238.2	238.4	234.6	225.3	205.9
201.1	216.0	224.3	228.3	228.2	224.3	216.2	201.1
192.6	205.3	211.5	213.1	213.2	209.9	204.7	193.5
182.9	187.4	190.9	192.5	192.5	190.6	186.4	182.6

Box Temperature Distribution

Top 137.4(epoxy) 146.4(under htr)

Right 139.2(epoxy) 143.3(under htr)

Left 137.2(epoxy) 143.0(under htr)

Bottom 130.1(epoxy) 137.0(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	198.0	217.9	194.8	221.9	201.4

Date: July 14 1991
Time: 08:27:18

Run ID No. 21APXXX250

Voltage:	88.1 Volts	Fill Gas:	Argon
Current:	3.40 Amps	Pressure:	15 psig
Power:	299.54 Watts		

Vessel Temperature: Box End - 61.5 deg C
TC End - 45.8 deg C

Heater Rod Temperature Distribution

208.6	223.3	230.9	233.1	233.4	231.8	222.4	208.1
220.1	238.4	247.9	251.7	252.6	248.2	237.2	217.9
221.6	---	252.6	257.3	257.9	251.5	241.8	221.2
218.8	239.7	250.5	255.9	254.0	250.5	240.2	219.9
216.6	234.9	244.9	248.3	248.7	244.5	234.8	214.5
209.6	225.2	234.0	238.1	238.0	234.0	225.4	209.6
200.9	214.2	220.8	222.5	222.7	219.2	213.6	201.7
190.7	195.7	199.4	201.1	201.1	199.2	194.5	190.5

Box Temperature Distribution

Top 143.1(epoxy) 152.6(under htr)

Right 145.0(epoxy) 149.3(under htr) Left 142.9(epoxy) 149.0(under htr)

Bottom 135.5(epoxy) 143.0(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	205.8	226.1	202.6	230.9	210.0

E.6 Above Atmospheric Pressure Helium Test Data

This section of Appendix E contains the Test Data collected on the experimental apparatus above atmospheric pressure (15 psig) in helium at 13 different Heater Rod power levels with the controlling temperature ranging from 70°C to 240°C without Boundary Condition Box side or end heaters operating. A Campaign Summary follows:

Vessel Pressure (psig)	Fill Gas	Box Temperature (deg C)	Central Heater Rod Temperature (deg C)	Run I.D. No.	Date Completed
15 psig	He	Not Controlled	70	21HPXXX070	6/14 7/1
			85	21HPXXX085	06/14/91
			100	21HPXXX100	06/15/91
			115	41HPXXX115	07/01/91
			125	21HPXXX125	06/16/91
			140	41HPXXX140	07/02/91
			150	21HPXXX150	06/16/91
			165	41HPXXX165	07/03/91
			175	21HPXXX175	06/17/91
			190	41HPXXX190	07/03/91
			200	21HPXXX200	06/17/91
			225	21HPXXX225	7/4 7/6
			240*	41HPXXX232	07/05/91
			250	21HPXXX250	canceled

* Control Setpoint was modified to 232°C due to the inability of the apparatus in its present electrical configuration to reach 240°C.

Date: June 14, 1991
Time: 11:32:08

Run ID No. 21HPXXX070

Voltage:	32.8 Volts	Fill Gas:	Helium
Current:	1.27 Amps	Pressure:	15 psig
Power:	41.656 Watts		

Vessel Temperature: Box End - 32.4 deg C
TC End - 29.1 deg C

Heater Rod Temperature Distribution

57.91	61.45	63.36	64.6	64.32	63.71	61.39	57.94
61.2	65.39	67.92	69.15	69.25	67.64	65.06	60.65
62.26	---	70.26	71.75	71.88	69.96	67.04	62.23
62.55	67.74	71.01	72.79	72.34	70.97	67.85	62.93
62.5	67.47	70.42	71.85	71.94	70.31	67.38	62.36
61.22	65.54	68.28	69.74	69.82	68.54	65.6	61.28
58.98	63.03	65.31	66.18	66.2	64.97	62.98	59.27
55.87	58.3	60.06	60.53	60.35	59.85	57.98	55.82

Box Temperature Distribution

Top 48.1(epoxy) 48.41(under htr)

Right 47.2(epoxy) 47.84(under htr)

Left 47.1(epoxy) 47.97(under htr)

Bottom 47.1(epoxy) 47.68(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	57.57	62.49	67.01	68.1	62.55

Date: July 1, 1991
Time: 15:53:33

Run ID No. 41HPXXX070

Voltage:	41.8 Volts	Fill Gas:	Helium
Current:	1.63 Amps	Pressure:	15 psig
Power:	68.134 Watts		

Vessel Temperature: Box End - 32.9 deg C
TC End - 29.6 deg C

Heater Rod Temperature Distribution

58.2	61.73	63.64	64.88	64.6	63.99	61.67	58.23
61.5	65.65	68.17	69.4	69.49	67.91	65.32	60.92
62.51	---	70.49	72.01	72.14	70.26	67.34	62.53
62.8	68.01	71.25	73.27	72.61	71.24	68.13	63.22
62.83	67.77	70.7	72.14	72.26	70.59	67.68	62.68
61.52	65.85	68.57	70.0	70.08	68.83	65.9	61.6
59.3	63.32	65.59	66.45	66.49	65.28	63.31	59.61
56.13	58.59	60.4	60.87	60.7	60.19	58.34	56.18

Box Temperature Distribution

Top 48.4(epoxy) 48.78(under htr)

Right 47.6(epoxy) 48.24(under htr)

Left 47.5(epoxy) 48.37(under htr)

Bottom 47.4(epoxy) 48.06(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	57.63	62.81	67.23	68.4	62.76

Date: June 14, 1991
Time: 20:24:13

Run ID No. 21HPXXX085

Voltage:	42.9 Volts	Fill Gas:	Helium
Current:	1.67 Amps	Pressure:	15 psig
Power:	71.643 Watts		

Vessel Temperature: Box End - 35.2 deg C
TC End - 31.2 deg C

Heater Rod Temperature Distribution

68.69	73.39	75.92	77.55	77.17	76.38	73.3	68.76
73.1	78.49	81.79	83.42	83.56	81.46	78.06	72.23
74.31	---	84.79	86.78	86.92	84.48	80.68	74.32
74.66	81.5	85.8	88.54	87.53	85.71	81.67	75.24
74.63	81.12	84.96	86.81	87.07	84.85	81.03	74.43
72.94	78.58	82.12	84.01	84.1	82.43	78.65	72.99
69.99	75.26	78.22	79.33	79.43	77.86	75.27	70.41
65.9	69.11	71.39	72.0	71.8	71.11	68.7	65.89

Box Temperature Distribution

Top 55.6(epoxy) 56.13(under htr)

Right 54.4(epoxy) 55.47(under htr)

Left 54.3(epoxy) 55.56(under htr)

Bottom 54.2(epoxy) 55.01(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	68.21	74.67	80.29	81.9	74.47

Date: June 15, 1991
Time: 13:24:17

Run ID No. 21HPXXX100

Voltage:	51.5 Volts	Fill Gas:	Helium
Current:	2.02 Amps	Pressure:	14 psig
Power:	104.03 Watts		

Vessel Temperature: Box End - 37.0 deg C
TC End - 32.0 deg C

Heater Rod Temperature Distribution

78.68	84.42	87.49	89.47	89.01	88.08	84.34	78.8
84.03	90.73	94.81	96.75	96.91	94.4	90.24	83.11
85.71	---	98.54	101.0	101.1	98.16	93.53	85.74
86.2	94.6	99.86	102.8	102.0	99.78	94.85	86.92
86.18	94.17	98.9	101.2	101.2	98.77	94.1	85.97
84.14	91.11	95.53	97.82	97.97	95.91	91.22	84.23
80.54	87.08	90.75	92.14	92.25	90.33	87.1	81.08
75.54	79.5	82.36	83.14	82.87	82.02	79.03	75.52

Box Temperature Distribution

Top 62.9(epoxy) 63.47(under htr)

Right 61.4(epoxy) 62.64(under htr)

Left 61.2(epoxy) 62.80(under htr)

Bottom 61.1(epoxy) 62.40(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	77.97	86.0	93.07	95.1	86.04

Date: July 1, 1991
Time: 23:39:04

Run ID No. 41HPXXX115

Voltage:	59.6 Volts	Fill Gas:	Helium
Current:	2.32 Amps	Pressure:	17 psig
Power:	138.272 Watts		

Vessel Temperature: Box End - 38.6 deg C
TC End - 33.3 deg C

Heater Rod Temperature Distribution

89.5	96.78	100.6	103.1	102.5	101.4	96.66	89.63
96.25	104.5	109.5	111.9	112.1	109.1	103.9	94.91
98.05	---	114.0	116.9	117.2	113.5	107.7	98.08
98.48	108.8	115.3	118.6	117.9	115.2	109.1	99.35
98.36	108.1	113.9	116.7	116.9	113.7	108.0	98.02
95.77	104.2	109.6	112.4	112.6	110.0	104.3	95.83
91.3	99.24	103.7	105.3	105.4	103.1	99.21	91.91
85.09	89.87	93.34	94.28	93.96	92.91	89.28	85.03

Box Temperature Distribution

Top 69.6(epoxy) 70.25(under htr)

Right 67.6(epoxy) 69.04(under htr)

Left 67.4(epoxy) 69.38(under htr)

Bottom 67.3(epoxy) 68.54(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	88.24	98.56	106.5	108.8	97.72

Date: June 16, 1991
Time: 10:50:18

Run ID No. 21HPXXX125

Voltage:	63.5 Volts	Fill Gas:	Helium
Current:	2.47 Amps	Pressure:	14 psig
Power:	156.845 Watts		

Vessel Temperature: Box End - 40.4 deg C
TC End - 34.2 deg C

Heater Rod Temperature Distribution

96.44	104.1	108.1	110.7	110.1	108.9	104.0	96.68
103.5	112.4	117.8	120.3	120.6	117.3	111.8	102.3
105.8	---	122.7	126.0	126.1	122.2	116.1	105.8
106.4	117.5	124.4	127.8	127.2	124.3	117.8	107.3
106.3	116.9	123.2	126.1	126.2	123.0	116.8	106.0
103.7	112.9	118.8	121.7	121.9	119.2	113.0	103.8
98.95	107.6	112.5	114.3	114.4	111.9	107.6	99.63
92.28	97.56	101.4	102.4	102.0	100.9	96.93	92.24

Box Temperature Distribution

Top 75.3(epoxy) 76.12(under htr)

Right 73.2(epoxy) 74.88(under htr) Left 73.0(epoxy) 75.16(under htr)

Bottom 72.9(epoxy) 74.37(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	95.26	106.0	115.1	117.6	106.0

Date: July 2, 1991
Time: 19:42:50

Run ID No. 41HPXXX140

Voltage:	67.9 Volts	Fill Gas:	Helium
Current:	2.64 Amps	Pressure:	13 psig
Power:	179.256 Watts		

Vessel Temperature: Box End - 43.2 deg C
TC End - 36.0 deg C

Heater Rod Temperature Distribution

107.7	116.4	120.9	123.8	123.1	121.8	116.3	107.9
116.2	125.8	131.8	134.6	134.9	131.2	125.1	114.5
118.5	---	137.5	141.0	141.3	136.9	130.1	118.5
119.2	131.7	139.5	143.4	142.6	139.4	132.1	120.3
119.3	131.2	138.3	141.6	141.7	138.1	131.1	119.0
116.4	126.8	133.4	136.8	137.0	133.9	126.9	116.4
110.9	120.9	126.3	128.4	128.6	125.8	120.9	111.8
103.5	109.5	113.9	115.0	114.6	113.3	108.8	103.4

Box Temperature Distribution

Top 83.8(epoxy) 84.83(under htr)

Right 81.4(epoxy) 83.39(under htr)

Left 81.1(epoxy) 83.72(under htr)

Bottom 81.0(epoxy) 82.80(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	106.1	118.5	128.8	132.1	118.8

Date: June 16, 1991
Time: 22:13:22

Run ID No. 21HPXXX150

Voltage:	71.1 Volts	Fill Gas:	Helium
Current:	2.77 Amps	Pressure:	15 psig
Power:	196.947 Watts		

Vessel Temperature: Box End - 43.5 deg C
TC End - 36.4 deg C

Heater Rod Temperature Distribution

114.3	124.0	129.1	132.3	131.5	130.1	123.9	114.7
123.6	134.4	141.0	144.2	144.5	140.5	133.6	121.7
126.0	---	147.1	151.0	151.2	146.4	138.9	126.1
126.7	140.5	149.1	153.3	152.5	148.9	141.0	127.9
126.7	139.9	147.6	151.1	151.4	147.4	139.8	126.3
123.4	134.9	142.1	145.8	146.0	142.6	135.0	123.5
117.4	128.3	134.2	136.5	136.7	133.6	128.3	118.3
109.1	115.7	120.5	121.7	121.3	119.9	114.9	108.9

Box Temperature Distribution

Top 87.3(epoxy) 88.49(under htr)

Right 84.6(epoxy) 86.84(under htr) Left 84.4(epoxy) 87.22(under htr)

Bottom 84.3(epoxy) 86.25(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	112.4	126.2	137.1	140.5	125.8

Date: July 3, 1991
Time: 14:27:46

Run ID No. 41HPXXX165

Voltage:	82.5 Volts	Fill Gas:	Helium
Current:	3.20 Amps	Pressure:	13 psig
Power:	264.0 Watts		

Vessel Temperature: Box End - 47.4 deg C
TC End - 39.0 deg C

Heater Rod Temperature Distribution

126.3	136.6	141.9	145.3	144.5	143.0	136.5	126.5
136.3	147.8	154.8	158.1	158.5	154.2	147.0	134.3
139.0	---	161.5	165.7	166.0	160.9	152.9	139.1
139.9	154.7	164.0	168.2	167.7	163.9	155.3	141.3
140.1	154.2	162.6	166.5	166.5	162.4	154.2	139.7
136.6	149.1	156.9	160.9	161.2	157.4	149.2	136.7
130.2	142.1	148.6	151.0	151.2	147.9	142.1	131.1
121.2	128.4	133.7	135.1	134.6	133.0	127.5	121.0

Box Temperature Distribution

Top 97.0(epoxy) 98.58(under htr)

Right 94.1(epoxy) 96.77(under htr) Left 93.9(epoxy) 97.14(under htr)

Bottom 93.8(epoxy) 96.13(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	124.0	138.8	150.9	154.5	139.3

Date: June 17, 1991
Time: 10:25:12

Run ID No. 21HPXXX175

Voltage:	80.8 Volts	Fill Gas:	Helium
Current:	3.17 Amps	Pressure:	15 psig
Power:	256.136 Watts		

Vessel Temperature: Box End - 47.4 deg C
TC End - 38.8 deg C

Heater Rod Temperature Distribution

133.5	144.8	150.7	154.4	153.5	151.9	144.7	133.9
144.6	157.0	164.8	168.5	168.9	164.2	156.2	142.3
147.4	---	172.1	176.8	177.0	171.3	162.5	147.4
148.2	164.4	174.5	179.4	178.5	174.4	165.0	149.7
148.4	163.8	172.9	177.2	177.3	172.7	163.7	147.8
144.5	158.0	166.6	170.9	171.3	167.2	158.1	144.6
137.5	150.4	157.4	160.1	160.4	156.6	150.4	138.6
127.6	135.4	141.2	142.7	142.3	140.5	134.6	127.5

Box Temperature Distribution

Top 101.3(epoxy) 102.9(under htr)

Right 97.9(epoxy) 100.8(under htr)

Left 97.7(epoxy) 101.3(under htr)

Bottom 97.6(epoxy) 100.1(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	131.0	147.1	159.9	163.8	147.2

Date: July 3, 1991
Time: 23:45:47

Run ID No. 41HPXXX190

Voltage:	89.2 Volts	Fill Gas:	Helium
Current:	3.48 Amps	Pressure:	16 psig
Power:	310.416 Watts		

Vessel Temperature: Box End - 50.2 deg C
TC End - 41.1 deg C

Heater Rod Temperature Distribution

145.0	157.4	163.9	167.9	166.9	165.2	157.3	145.4
156.9	170.8	179.2	183.3	183.7	178.6	169.9	154.5
160.1	---	187.2	192.3	192.6	186.3	176.8	160.1
161.0	178.8	189.9	195.1	194.3	189.8	179.5	162.6
161.1	178.1	188.1	192.7	192.8	187.8	178.0	160.5
156.8	171.7	181.1	185.9	186.2	181.7	171.8	156.9
149.3	163.3	171.1	173.9	174.2	170.1	163.3	150.3
138.4	146.9	153.2	154.8	154.3	152.4	145.9	138.2

Box Temperature Distribution

Top 109.1(epoxy) 111.2(under htr)

Right 105.5(epoxy) 108.9(under htr) Left 105.3(epoxy) 109.4(under htr)

Bottom 105.2(epoxy) 108.1(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	142.1	159.7	173.3	177.6	159.5

Date: June 17, 1991
Time: 18:33:36

Run ID No. 21HPXXX200

Voltage:	99.2 Volts	Fill Gas:	Helium
Current:	3.86 Amps	Pressure:	16 psig
Power:	382.912 Watts		

Vessel Temperature: Box End - 50.7 deg C
TC End - 41.1 deg C

Heater Rod Temperature Distribution

151.8	165.0	171.8	176.1	175.0	173.2	164.9	152.3
164.4	179.2	188.2	192.5	193.0	187.6	178.3	162.0
167.9	---	196.7	202.1	202.4	195.8	185.7	168.0
168.9	187.9	199.7	205.4	204.4	199.6	188.6	170.6
169.2	187.2	197.9	202.8	203.0	197.7	187.2	168.5
164.7	180.5	190.5	195.6	196.0	191.1	180.7	164.8
156.6	171.6	179.9	182.9	183.3	179.0	171.7	157.8
145.2	154.2	161.0	162.7	162.2	160.1	153.2	145.0

Box Temperature Distribution

Top 114.0(epoxy) 116.1(under htr)

Right 109.8(epoxy) 113.6(under htr) Left 109.6(epoxy) 114.1(under htr)

Bottom 109.6(epoxy) 112.7(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	148.7	167.2	181.7	186.4	167.2

Date: July 4, 1991
Time: 22:49:05

Run ID No. 21HPXXX225

Voltage:	111.1 Volts	Fill Gas:	Helium
Current:	4.30 Amps	Pressure:	15 psig
Power:	477.73 Watts		

Vessel Temperature: Box End - 56.7 deg C
TC End - 45.2 deg C

Heater Rod Temperature Distribution

171.6	185.7	193.1	197.7	196.5	194.7	185.7	172.0
185.3	201.5	211.1	215.8	216.3	210.5	200.5	182.7
189.4	---	220.7	226.5	226.9	219.8	208.8	189.4
190.6	211.5	224.3	230.1	229.4	224.2	212.3	192.5
191.0	210.8	222.6	227.9	227.9	222.4	210.9	190.3
186.3	203.8	214.9	220.4	220.9	215.5	204.0	186.4
177.6	194.3	203.4	206.9	207.2	202.5	194.3	178.8
165.0	175.1	182.6	184.5	184.0	181.7	174.0	164.8

Box Temperature Distribution

Top 130.8(epoxy) 133.1(under htr)

Right 125.9(epoxy) 130.4(under htr)

Left 125.7(epoxy) 131.0(under htr)

Bottom 125.7(epoxy) 129.2(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	168.1	187.7	203.9	209.0	188.8

Date: July 6 1991
Time: 12:51:25

Run ID No. 21HPXXX225

Voltage:	111.1 Volts	Fill Gas:	Helium
Current:	4.29 Amps	Pressure:	14 psig
Power:	476.619 Watts		

Vessel Temperature: Box End - 56.9 deg C
TC End - 45.0 deg C

Heater Rod Temperature Distribution

171.8	185.8	193.1	197.7	196.5	194.7	185.8	172.2
185.5	201.6	211.2	215.9	216.4	210.6	200.7	183.0
189.7	---	221.0	226.8	227.2	220.0	209.1	189.7
190.9	211.8	224.7	230.3	229.7	224.5	212.7	192.8
191.4	211.2	223.1	228.4	228.3	222.8	211.3	190.7
186.7	204.3	215.4	220.9	221.4	216.0	204.4	186.8
178.1	194.8	204.0	207.5	207.8	203.1	194.9	179.3
165.6	175.8	183.3	185.2	184.7	182.3	174.6	165.3

Box Temperature Distribution

Top 131.3(epoxy) 133.6(under htr)

Right 126.7(epoxy) 131.1(under htr) Left 126.5(epoxy) 131.6(under htr)

Bottom 126.4(epoxy) 129.9(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	168.2	187.8	204.4	209.4	189.4

Date: July 5, 1991
Time: 20:55:22

Run ID No. 41HPXXX232

Voltage:	122.9 Volts	Fill Gas:	Helium
Current:	4.74 Amps	Pressure:	16 psig
Power:	582.546 Watts		

Vessel Temperature: Box End - 56.6 deg C
TC End - 45.0 deg C

Heater Rod Temperature Distribution

175.2	190.2	197.9	202.8	201.5	199.6	190.1	175.7
189.6	206.7	216.8	221.7	222.3	216.2	205.7	187.0
194.0	---	226.8	232.9	233.2	225.9	214.3	193.9
195.1	217.1	230.4	236.8	235.8	230.3	217.9	197.2
195.7	216.4	228.7	234.2	234.3	228.5	216.5	194.9
190.6	209.0	220.5	226.2	226.7	221.2	209.2	190.7
181.5	199.0	208.5	212.1	212.4	207.5	199.0	182.8
168.3	178.9	186.8	188.7	188.2	185.7	177.7	168.1

Box Temperature Distribution

Top 132.4(epoxy) 134.8(under htr)

Right 127.4(epoxy) 132.0(under htr)

Left 127.2(epoxy) 132.6(under htr)

Bottom 127.2(epoxy) 130.8(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	171.6	192.2	208.8	214.4	192.9

E.7 Below Atmospheric Pressure Test Data #1

This section of Appendix E contains the Test Data collected on the experimental apparatus below atmospheric pressure (24 inches Hg) at 14 different Heater Rod power levels with the controlling temperature ranging from 70°C to 250°C without Boundary Condition Box side or end heaters operating. A Campaign Summary follows:

Vessel Pressure (in Hg)	Fill Gas	Box Temperature (deg C)	Central Heater Rod Temperature (deg C)	Run I.D. No.	Date Completed
24 in Hg	Air	Not Controlled	70	31XVXXX070	07/22/91
			85	31XVXXX085	07/23/91
			100	31XVXXX100	7/23 7/28
			125	31XVXXX125	7/24 7/29
			140	42XVXXX140	07/29/91
			150	31XVXXX150	07/25/91
			165	42XVXXX165	07/30/91
			175	31XVXXX175	07/25/91
			190	42XVXXX190	07/31/91
			200	31XVXXX200	07/26/91
			215	42XVXXX215	07/31/91
			225	31XVXXX225	07/27/91
			240	42XVXXX240	8/2 8/3
			250	31XVXXX250	07/27/91

Date: July 22, 1991
Time: 12:33:43

Run ID No. 31XVXXX070

Voltage:	12.1 Volts	Fill Gas:	Air
Current:	0.46 Amps	Pressure:	26 in Hg
Power:	5.566 Watts		

Vessel Temperature: Box End - 37.6 deg C
TC End - 30.4 deg C

Heater Rod Temperature Distribution

63.34	65.26	66.32	66.88	66.73	66.42	65.1	63.07
65.15	67.98	69.54	70.21	70.31	69.44	67.79	65.03
66.11	---	71.37	72.17	72.37	71.17	69.38	66.06
66.29	69.91	72.07	73.38	72.96	72.08	70.07	66.52
66.47	69.94	72.0	72.94	72.96	72.04	69.93	66.34
65.71	68.82	70.81	71.78	71.89	70.99	69.0	65.86
64.48	67.32	68.93	69.56	69.53	68.7	67.23	64.59
62.47	64.13	65.35	65.72	65.65	65.21	64.03	62.58

Box Temperature Distribution

Top 55.6(epoxy) 57.22(under htr)

Right 56.6(epoxy) 57.01(under htr) Left 56.2(epoxy) 57.17(under htr)

Bottom 54.9(epoxy) 56.78(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	63.21	66.68	68.16	70.9	67.3

Date: July 23, 1991
Time: 01:08:02

Run ID No. 31XVXXX085

Voltage:	15.5 Volts	Fill Gas:	Air
Current:	0.58 Amps	Pressure:	26 in Hg
Power:	8.99 Watts		

Vessel Temperature: Box End - 40.5 deg C
TC End - 31.4 deg C

Heater Rod Temperature Distribution

74.88	77.41	78.78	79.51	79.32	78.93	77.21	74.56
77.33	80.97	82.98	83.85	83.98	82.85	80.75	77.11
78.51	---	85.34	86.44	86.64	85.13	82.81	78.49
78.82	83.52	86.3	87.71	87.4	86.3	83.71	79.08
78.95	83.49	86.16	87.37	87.3	86.21	83.49	78.77
78.0	82.05	84.62	85.86	86.01	84.85	82.27	78.16
76.38	80.1	82.2	83.0	82.91	81.86	79.94	76.49
73.72	75.92	77.49	77.97	77.86	77.29	75.76	73.84

Box Temperature Distribution

Top 64.7(epoxy) 66.83(under htr)

Right 65.8(epoxy) 66.50(under htr)

Left 65.4(epoxy) 66.79(under htr)

Bottom 63.9(epoxy) 66.06(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	74.73	79.26	81.08	84.6	80.05

Date: July 23, 1991
Time: 15:34:16

Run ID No. 31XVXXX100

Voltage:	18.1 Volts	Fill Gas:	Air
Current:	0.70 Amps	Pressure:	26 in Hg
Power:	12.67 Watts		

Vessel Temperature: Box End - 45.3 deg C
TC End - 33.4 deg C

Heater Rod Temperature Distribution

87.37	90.38	92.02	92.89	92.65	92.2	90.16	87.02
90.36	94.65	97.07	98.08	98.24	96.92	94.38	90.07
91.75	---	99.9	101.2	101.5	99.61	96.87	91.7
92.1	97.69	101.0	102.8	102.4	101.0	97.94	92.42
92.32	97.73	100.9	102.4	102.4	101.0	97.74	92.13
91.23	96.04	99.14	100.6	100.8	99.39	96.3	91.41
89.3	93.73	96.24	97.21	97.2	95.94	93.65	89.52
86.29	88.87	90.75	91.34	91.21	90.52	88.69	86.4

Box Temperature Distribution

Top 75.2(epoxy) 77.99(under htr)

Right 76.7(epoxy) 77.62(under htr)

Left 76.1(epoxy) 77.93(under htr)

Bottom 74.3(epoxy) 77.13(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	87.2	92.59	94.76	98.9	93.6

Date: July 28, 1991
Time: 14:16:27

Run ID No. 31XVXXX100

Voltage:	20.8 Volts	Fill Gas:	Air
Current:	0.81 Amps	Pressure:	23 in Hg
Power:	16.848 Watts		

Vessel Temperature: Box End - 38.6 deg C
TC End - 31.1 deg C

Heater Rod Temperature Distribution

82.07	86.42	88.69	89.96	89.62	88.95	86.09	81.69
86.33	92.09	95.38	96.84	97.01	95.17	91.67	85.65
87.87	---	98.89	100.7	100.9	98.51	94.71	87.77
88.29	95.68	100.1	102.4	101.9	100.1	95.92	88.64
88.33	95.49	99.62	101.5	101.6	99.6	95.38	88.03
86.75	93.08	96.95	98.84	98.99	97.21	93.26	86.85
83.98	89.71	92.88	94.05	94.08	92.46	89.57	84.27
79.93	83.23	85.54	86.26	86.07	85.26	82.89	79.97

Box Temperature Distribution

Top 66.5(epoxy) 68.84(under htr)

Right 67.3(epoxy) 68.18(under htr)

Left 66.7(epoxy) 68.51(under htr)

Bottom 64.9(epoxy) 67.16(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	81.95	89.22	91.97	97.2	89.46

Date: July 24, 1991
Time: 13:20:09

Run ID No. 31XVXXX125

Voltage:	22.7 Volts	Fill Gas:	Air
Current:	0.88 Amps	Pressure:	26 in Hg
Power:	19.976 Watts		

Vessel Temperature: Box End - 52.4 deg C
TC End - 35.1 deg C

Heater Rod Temperature Distribution

108.2	112.0	114.1	115.2	114.9	114.4	111.8	107.8
112.2	117.5	120.5	121.8	122.0	120.4	117.2	111.7
113.8	---	124.1	125.8	126.1	123.8	120.3	113.8
114.3	121.4	125.6	127.8	127.3	125.6	121.7	114.7
114.6	121.5	125.5	127.3	127.4	125.6	121.5	114.3
113.2	119.3	123.3	125.1	125.4	123.6	119.7	113.5
110.9	116.5	119.7	120.9	120.9	119.3	116.4	111.2
107.1	110.4	112.8	113.5	113.4	112.5	110.1	107.2

Box Temperature Distribution

Top 92.3(epoxy) 96.41(under htr)

Right 94.6(epoxy) 95.99(under htr)

Left 93.6(epoxy) 96.34(under htr)

Bottom 91.2(epoxy) 95.20(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	107.9	114.7	117.4	122.7	116.1

Date: July 29, 1991
Time: 01:04:15

Run ID No. 31XVXXX125

Voltage:	25.5 Volts	Fill Gas:	Air
Current:	1.00 Amps	Pressure:	25 in Hg
Power:	25.5 Watts		

Vessel Temperature: Box End - 44.8 deg C
TC End - 33.3 deg C

Heater Rod Temperature Distribution

102.3	107.7	110.5	112.0	111.6	110.8	107.3	101.9
107.8	114.8	118.9	120.7	120.9	118.7	114.4	106.9
109.7	---	123.4	125.6	125.9	122.9	118.3	109.6
110.3	119.6	125.0	127.5	127.2	125.0	119.9	110.8
110.4	119.4	124.6	126.9	126.7	124.6	119.4	110.1
108.6	116.6	121.5	123.9	124.1	121.9	116.9	108.7
105.2	112.5	116.6	118.1	118.1	116.0	112.3	105.5
100.1	104.4	107.3	108.3	108.0	107.0	104.0	100.2

Box Temperature Distribution

Top 82.4(epoxy) 85.92(under htr)

Right 83.8(epoxy) 85.52(under htr)

Left 83.1(epoxy) 85.88(under htr)

Bottom 80.6(epoxy) 84.19(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	102.1	111.2	114.8	121.3	112.2

Date: July 29, 1991
Time: 14:24:44

Run ID No. 42XVXXX140

Voltage:	32.2 Volts	Fill Gas:	Air
Current:	1.26 Amps	Pressure:	25 in Hg
Power:	40.572 Watts		

Vessel Temperature: Box End - 46.1 deg C
TC End - 33.6 deg C

Heater Rod Temperature Distribution

114.1	120.3	123.5	125.3	124.8	123.9	119.9	113.6
120.3	128.5	133.2	135.2	135.5	132.9	128.0	119.4
122.6	---	138.3	140.9	141.2	137.9	132.5	122.5
123.3	133.9	140.2	143.1	142.7	140.2	134.4	123.9
123.4	133.8	139.8	142.3	142.2	139.8	133.7	123.0
121.3	130.5	136.2	138.8	139.1	136.5	130.8	121.5
117.5	125.9	130.5	132.2	132.2	129.9	125.7	117.9
111.5	116.5	119.9	121.0	120.7	119.5	116.0	111.6

Box Temperature Distribution

Top 90.3(epoxy) 94.5(under htr)

Right 91.9(epoxy) 93.96(under htr)

Left 90.9(epoxy) 94.26(under htr)

Bottom 88.2(epoxy) 92.3(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	113.7	124.2	128.1	135.8	125.3

Date: July 25, 1991
Time: 14:25:59

Run ID No. 31XVXXX150

Voltage:	29.6 Volts	Fill Gas:	Air
Current:	1.14 Amps	Pressure:	26 in Hg
Power:	33.744 Watts		

Vessel Temperature: Box End - 58.1 deg C
TC End - 37.4 deg C

Heater Rod Temperature Distribution

128.1	133.1	135.8	137.2	136.8	136.1	132.8	127.6
133.4	140.2	144.2	145.9	146.1	144.0	139.8	132.7
135.5	---	148.8	150.9	151.3	148.4	143.9	135.4
136.1	145.3	150.7	153.3	152.9	150.7	145.7	136.6
136.4	145.3	150.6	152.8	152.9	150.6	145.4	136.1
134.7	142.6	147.7	150.0	150.3	148.0	143.0	135.0
131.5	138.9	143.0	144.5	144.6	142.6	138.8	132.0
126.7	130.9	134.0	135.0	134.8	133.7	130.6	126.8

Box Temperature Distribution

Top 107.9(epoxy) 112.7(under htr)

Right 109.6(epoxy) 112.0(under htr)

Left 108.2(epoxy) 112.0(under htr)

Bottom 105.7(epoxy) 110.2(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	127.8	136.6	140.1	147.0	138.5

Date: July 30, 1991
Time: 12:22:46

Run ID No. 42XVXXX165

Voltage:	38.3 Volts	Fill Gas:	Air
Current:	1.50 Amps	Pressure:	23 in Hg
Power:	57.45 Watts		

Vessel Temperature: Box End - 50.7 deg C
TC End - 36.7 deg C

Heater Rod Temperature Distribution

134.2	141.7	145.6	147.6	147.1	146.1	141.3	133.7
141.6	151.5	157.1	159.5	159.9	156.8	150.9	140.6
144.4	---	163.1	166.3	166.6	162.6	156.3	144.4
145.3	157.9	165.4	169.1	168.5	165.4	158.5	145.9
145.5	157.8	165.0	167.9	168.1	164.9	157.7	144.9
142.9	153.8	160.6	163.8	164.0	161.0	154.2	143.1
138.3	148.4	153.8	155.8	155.9	153.1	148.2	138.8
131.3	137.1	141.3	142.5	142.3	140.8	136.6	131.3

Box Temperature Distribution

Top 105.7(epoxy) 111.0(under htr)

Right 107.2(epoxy) 109.9(under htr) Left 105.9(epoxy) 110.2(under htr)

Bottom 102.4(epoxy) 107.7(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	133.6	146.2	150.5	159.7	147.5

Date: July 25, 1991
Time: 22:35:41

Run ID No. 31XVXXX175

Voltage:	35.4 Volts	Fill Gas:	Air
Current:	1.37 Amps	Pressure:	25 in Hg
Power:	48.498 Watts		

Vessel Temperature: Box End - 64.0 deg C
TC End - 40.3 deg C

Heater Rod Temperature Distribution

148.0	154.1	157.5	159.2	158.7	157.9	153.8	147.4
154.7	162.9	167.8	169.9	170.2	167.6	162.5	153.6
157.0	---	173.5	176.2	176.6	173.0	167.5	156.9
157.9	169.1	175.8	178.9	178.5	175.8	169.7	158.4
158.2	169.2	175.7	178.4	178.4	175.7	169.2	157.7
156.0	165.8	172.1	175.0	175.3	172.5	166.3	156.3
152.2	161.3	166.3	168.2	168.2	165.7	161.1	152.6
146.2	151.4	155.2	156.3	156.1	154.7	151.0	146.3

Box Temperature Distribution

Top 121.9(epoxy) 127.9(under htr)

Right 124.8(epoxy) 127.6(under htr) Left 123.1(epoxy) 127.7(under htr)

Bottom 120.1(epoxy) 125.5(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	147.5	158.2	162.4	170.6	160.7

Date: July 31, 1991
Time: 01:43:40

Run ID No. 42XVXXX190

Voltage:	44.1 Volts	Fill Gas:	Air
Current:	1.71 Amps	Pressure:	24 in Hg
Power:	75.411 Watts		

Vessel Temperature: Box End - 58.7 deg C
TC End - 39.6 deg C

Heater Rod Temperature Distribution

156.4	164.3	168.5	170.8	170.2	169.1	164.0	155.8
164.6	175.2	181.3	184.0	184.4	181.1	174.7	163.4
167.7	---	188.2	191.7	192.0	187.6	180.7	167.6
168.6	182.6	190.9	195.0	194.3	190.9	183.3	169.4
169.1	182.7	190.6	194.0	194.2	190.7	182.7	168.4
166.4	178.5	186.1	189.6	189.9	186.6	178.9	166.6
161.5	172.7	178.8	181.0	181.2	178.1	172.5	162.1
154.0	160.5	165.1	166.5	166.2	164.6	159.9	154.1

Box Temperature Distribution

Top 124.7(epoxy) 131.2(under htr)

Right 127.1(epoxy) 130.4(under htr)

Left 125.3(epoxy) 130.7(under htr)

Bottom 121.2(epoxy) 127.8(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	155.6	169.0	174.0	184.2	171.4

Date: July 26, 1991
Time: 11:52:48

Run ID No. 31XVXXX200

Voltage:	44.5 Volts	Fill Gas:	Air
Current:	1.72 Amps	Pressure:	25 in Hg
Power:	76.54 Watts		

Vessel Temperature: Box End - 67.3 deg C
TC End - 41.6 deg C

Heater Rod Temperature Distribution

167.9	175.3	179.3	181.4	180.8	179.8	174.9	167.3
175.8	185.8	191.7	194.2	194.5	191.4	185.3	174.6
178.7	---	198.5	201.7	202.1	197.8	191.2	178.6
179.7	193.2	201.2	205.1	204.4	201.2	193.9	180.4
180.2	193.3	201.1	204.3	204.5	201.2	193.4	179.5
177.6	189.4	196.8	200.2	200.6	197.3	189.9	178.0
173.1	184.0	190.0	192.2	192.3	189.3	183.8	173.7
166.0	172.2	176.7	178.1	177.9	176.2	171.7	166.1

Box Temperature Distribution

Top 136.3(epoxy) 144.3(under htr)

Right 139.8(epoxy) 143.5(under htr)

Left 137.8(epoxy) 143.5(under htr)

Bottom 133.9(epoxy) 140.6(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	167.0	179.7	184.5	194.4	182.7

Date: July 31, 1991
Time: 16:33:35

Run ID No. 42XVXXX215

Voltage:	53.7 Volts	Fill Gas:	Air
Current:	2.08 Amps	Pressure:	23 in Hg
Power:	111.696 Watts		

Vessel Temperature: Box End - 63.1 deg C
TC End - 41.5 deg C

Heater Rod Temperature Distribution

176.1	185.2	189.9	192.5	191.8	190.7	184.8	175.6
185.3	197.6	204.5	207.6	208.0	204.4	197.0	184.2
189.0	---	212.3	216.4	216.6	211.8	204.0	189.1
190.3	206.2	215.6	220.4	219.4	215.5	206.9	191.1
190.9	206.3	215.4	219.0	219.5	215.4	206.3	190.0
187.8	201.7	210.2	214.2	214.6	210.7	202.1	188.1
182.3	195.1	202.0	204.5	204.8	201.3	194.9	183.0
173.9	181.2	186.4	188.0	187.8	185.9	180.5	173.9

Box Temperature Distribution

Top 140.1(epoxy) 147.9(under htr)

Right 142.4(epoxy) 146.6(under htr)

Left 140.4(epoxy) 146.9(under htr)

Bottom 135.5(epoxy) 143.3(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	175.1	190.1	195.4	207.3	192.9

Date: July 27, 1991
Time: 00:02:47

Run ID No. 31XVXXX225

Voltage:	54.3 Volts	Fill Gas:	Air
Current:	2.11 Amps	Pressure:	25 in Hg
Power:	114.573 Watts		

Vessel Temperature: Box End - 72.4 deg C
TC End - 45.1 deg C

Heater Rod Temperature Distribution

188.2	196.8	201.3	203.7	203.0	202.0	196.4	187.6
197.4	208.8	215.5	218.3	218.8	215.3	208.3	196.0
200.7	---	223.2	226.9	227.3	222.6	215.1	200.7
201.8	217.3	226.5	230.9	230.1	226.3	218.1	202.8
202.6	217.5	226.4	230.0	230.4	226.4	217.6	201.8
199.7	213.1	221.6	225.4	225.8	222.1	213.7	200.1
194.5	207.0	213.8	216.3	216.5	213.1	206.8	195.2
186.5	193.6	198.8	200.3	200.1	198.2	193.0	186.6

Box Temperature Distribution

Top 152.2(epoxy) 161.0(under htr)

Right 155.7(epoxy) 160.1(under htr) Left 153.3(epoxy) 160.3(under htr)

Bottom 148.8(epoxy) 156.9(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	187.0	201.3	206.6	218.2	205.0

Date: August 2, 1991
Time: 21:58:52

Run ID No. 42XVXXX240

Voltage:	59.5 Volts	Fill Gas:	Air
Current:	2.29 Amps	Pressure:	23 in Hg
Power:	136.255 Watts		

Vessel Temperature: Box End - 75.0 deg C
TC End - 47.3 deg C

Heater Rod Temperature Distribution

200.2	209.5	214.4	217.0	216.3	215.2	209.2	199.5
210.0	222.6	229.8	232.9	233.4	229.7	222.0	208.6
213.7	---	238.1	242.1	242.6	237.4	229.3	213.6
214.9	231.7	241.5	246.0	245.4	241.5	232.5	215.9
215.6	231.8	241.3	245.2	245.4	241.4	231.9	214.7
212.5	227.1	236.2	240.3	240.7	236.7	227.6	212.8
206.9	220.4	227.8	230.4	230.5	226.9	220.1	207.5
198.0	205.9	211.4	213.1	212.8	210.8	205.1	198.1

Box Temperature Distribution

Top 160.6(epoxy) 170.3(under htr)

Right 164.2(epoxy) 169.1(under htr)

Left 161.8(epoxy) 169.5(under htr)

Bottom 156.3(epoxy) 165.6(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	198.4	214.0	219.6	231.6	217.4

Date: August 3, 1991
Time: 11:24:06

Run ID No. 42XVXXX240

Voltage:	60.9 Volts	Fill Gas:	Air
Current:	2.35 Amps	Pressure:	22 in Hg
Power:	143.115 Watts		

Vessel Temperature: Box End - 72.6 deg C
TC End - 46.4 deg C

Heater Rod Temperature Distribution

198.9	208.5	213.5	216.2	215.4	214.3	208.1	198.3
208.9	221.7	229.1	232.3	232.9	229.0	221.2	207.5
212.7	---	237.6	241.5	242.2	236.9	228.6	212.6
213.9	230.9	241.0	245.7	244.9	241.0	231.9	214.9
214.6	231.0	240.7	244.7	244.9	240.8	231.1	213.7
211.4	226.2	235.5	239.6	240.1	235.9	226.7	211.7
205.6	219.4	226.9	229.5	229.6	225.9	219.0	206.2
196.5	204.6	210.2	211.8	211.6	209.5	203.8	196.7

Box Temperature Distribution

Top 159.1(epoxy) 168.4(under htr)

Right 162.1(epoxy) 167.1(under htr)

Left 159.8(epoxy) 167.5(under htr)

Bottom 154.2(epoxy) 163.4(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	197.1	213.0	218.7	231.1	216.4

Date: July 27, 1991
Time: 11:07:13

Run ID No. 31XVXXX250

Voltage:	63.4 Volts	Fill Gas:	Air
Current:	2.44 Amps	Pressure:	24 in Hg
Power:	154.696 Watts		

Vessel Temperature: Box End - 77.5 deg C
TC End - 48.0 deg C

Heater Rod Temperature Distribution

208.8	218.3	223.4	226.1	225.3	224.1	217.9	208.1
219.1	231.7	239.1	242.3	242.9	239.0	231.2	217.4
222.7	---	247.7	251.8	252.2	246.9	238.7	222.5
223.8	241.1	251.3	256.0	255.2	251.2	242.0	224.9
224.7	241.3	251.1	255.1	255.3	251.2	241.4	223.8
221.5	236.5	245.9	250.1	250.5	246.4	237.0	221.8
215.8	229.7	237.3	240.0	240.2	236.4	229.5	216.5
206.7	214.8	220.5	222.2	222.0	219.9	214.1	206.8

Box Temperature Distribution

Top 167.6(epoxy) 177.9(under htr)

Right 171.4(epoxy) 176.6(under htr)

Left 168.4(epoxy) 176.9(under htr)

Bottom 163.2(epoxy) 173.0(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	207.3	222.7	228.4	240.8	226.8

E.8 Below Atmospheric Pressure Test Data #2

This section of Appendix E contains the Test Data collected on the experimental apparatus below atmospheric pressure at 16 inches Hg and 20 inches Hg at the same Heater Rod controlling temperature of 240°C without Boundary Condition Box side or end heaters operating. The purpose of these data points are discussed in Chapter 5 Section 5. The summary follows:

Vessel Pressure (in Hg)	Fill Gas	Box Temperature (deg C)	Central Heater Rod Temperature (deg C)	Run I.D. No.	Date Completed
16 in Hg	Air	Not Controlled	240	42XVXXX240	08/08/91
20 in Hg	Air	Not Controlled	240	42XVXXX240	08/02/91

Date: August 8, 1991
Time: 04:29:58

Run ID No. 42XVXXX240

Voltage:	64.8 Volts	Fill Gas:	Air
Current:	2.50 Amps	Pressure:	16 in Hg
Power:	162.0 Watts		

Vessel Temperature: Box End - 64.3 deg C
TC End - 44.5 deg C

Heater Rod Temperature Distribution

193.9	205.3	211.2	214.3	213.5	212.1	204.8	193.3
205.1	220.1	228.6	232.2	232.8	228.4	219.3	203.4
209.1	---	237.3	241.8	242.5	236.5	227.1	208.9
210.0	229.3	240.5	245.6	244.7	240.4	230.1	211.2
210.5	228.9	239.5	243.8	244.0	239.4	228.7	209.2
206.6	223.1	233.1	237.6	238.0	233.3	223.2	206.6
199.8	214.9	223.0	225.8	225.9	221.7	214.3	200.3
189.5	198.1	204.2	206.1	205.9	203.6	197.1	189.5

Box Temperature Distribution

Top 150.4(epoxy) 158.5(under htr)

Right 151.7(epoxy) 156.8(under htr)

Left 149.6(epoxy) 157.2(under htr)

Bottom 143.8(epoxy) 152.7(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	192.0	210.3	215.6	229.2	211.6

Date: August 2, 1991
Time: 14:05:48

Run ID No. 42XVXXX240

Voltage:	65.1 Volts	Fill Gas:	Air
Current:	2.52 Amps	Pressure:	20 in Hg
Power:	164.052 Watts		

Vessel Temperature: Box End - 67.8 deg C
TC End - 45.6 deg C

Heater Rod Temperature Distribution

196.1	206.7	212.1	215.1	214.3	213.0	206.3	195.5
206.9	220.8	228.8	232.3	232.8	228.7	220.2	205.3
210.8	---	237.5	242.1	242.4	236.8	228.0	210.7
211.9	230.2	241.0	246.0	245.1	240.8	231.2	213.1
212.6	230.2	240.5	244.6	244.8	240.4	230.2	211.5
209.0	224.9	234.6	239.0	239.4	235.0	225.2	209.2
202.7	217.3	225.2	227.9	228.1	224.1	216.9	203.3
193.0	201.4	207.3	209.1	208.9	206.7	200.5	192.9

Box Temperature Distribution

Top 154.2(epoxy) 163.0(under htr)

Right 156.1(epoxy) 161.2(under htr)

Left 154.2(epoxy) 161.6(under htr)

Bottom 148.2(epoxy) 157.3(under htr)

End of Heater Rod Temperature Distribution

Position	1-1	2-7	4-4	5-5	7-3
Temperature (deg C)	194.3	211.5	217.1	230.1	214.3

APPENDIX F

PROCESS FOR DATA REDUCTION

This appendix contains the process of data reduction used for the data taken above atmospheric pressure in Helium and in Argon and the data taken below atmospheric pressure. Chapter 5 presents the overall scheme of analysis/reduction of the data taken in each Test Campaign and specifically goes through the process of data reduction for the data taken at atmospheric pressure in Air and above atmospheric pressure in Nitrogen. The processes of this appendix are presented in the following order:

F.1 Above Atmospheric Pressure Argon Data Reduction

This section of Appendix F provides the detailed process of reduction for the Argon data set. The Argon data set includes the data taken above atmospheric pressure with nitrogen as the heat transfer medium (Appendix E.5).

Argon Test Data Reduction Step 1.

In Step 1, the average wall temperature as a function of power is obtained for the Argon data. Using Cricket Graph, the actual power and average wall temperature obtained from the experimental apparatus for Argon are input into a data file. The data is then plotted in the form of Average Wall Temperature (y-axis) as a function of Power (x-axis) and a second order polynomial curve fit of this data provides the function input for Step 3. The plotted Argon data with the curve fit is provided in Figure F-1. The input function for Argon is:

$$y = 42.645 + 0.60389\,x - 8.6181(10)^{-4}\,x^2$$

where x is power and y is the average wall temperature.

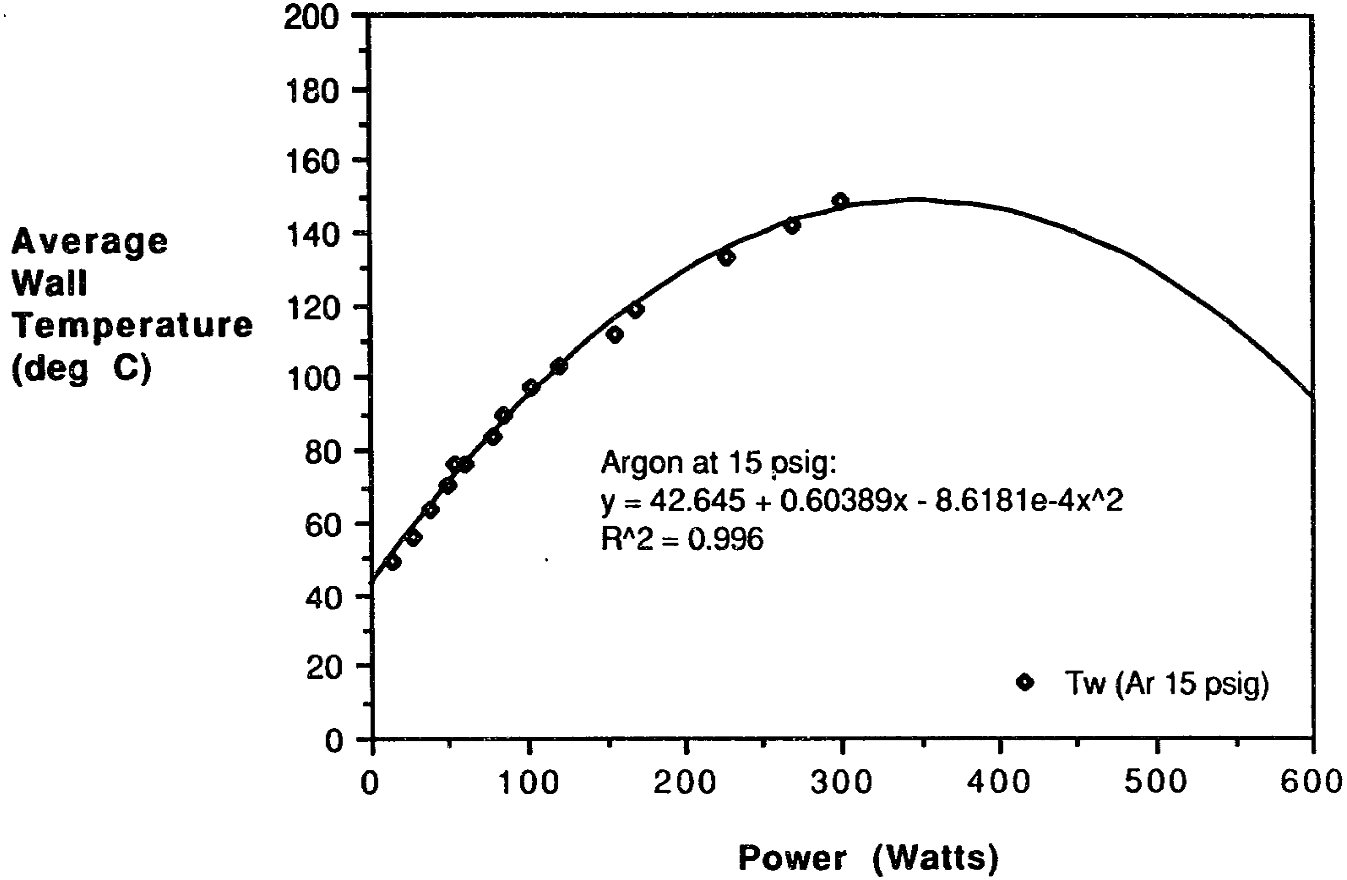


Figure F-1: Average Wall Temperature as a function of Power in Pressurized Argon (15 psig)

Argon Test Data Reduction Step 2.

In Step 2, the Wooten-Epstein relationship only applies to the Air/Nitrogen data set. Go to Step 3.

Argon Test Data Reduction Step 3.

In Step 3, the lumped k_{eff}/h_{edge} model is evaluated to provide a predicted differential temperature between the maximum heater rod temperature and the average wall temperature as a function of power for the Argon test data. Using Mathematica, the function obtained from Step 1 is input into the "mit8x8.m", "mit8x8.up" and "mit8x8.lo" programs in the following format:

42.645 + 0.60389 Q - 0.00086181 Q Q + 273

in the Input Section. Adding 273 converts the experimental temperature units (°C) to the units used in the theoretical prediction calculations (°K). Additionally, the heat transfer medium (Ar) is input into each "mit8x8" program. The user should also ensure that the appropriate "Fcond" factor is available in each "mit8x8" program. Available means that the appropriate factor is not surrounded by comment characters, "(*" on the left side of "Fcond" for Ar and a second "*)" at the end of the line. After inputting these items, the lumped k_{eff}/h_{edge} model programs are ready to be executed/evaluated. First execute "gas.m"; second execute "keff.m"; third execute "mit8x8.m"; fourth execute "mit8x8.up"; and lastly execute "mit8x8.lo". The output results from "mit8x8.m", "mit8x8.up" and "mit8x8.lo" are in table form providing the Heat Transfer Medium (N2) in the first column, Power in the second column, and the Predicted Differential Temperature in the third column. Note: $\Delta T(°K) = \Delta T(°C)$. The "mit8x8.m" program with its output results is provided in Table F-1; the "mit8x8.up" program with its output results is provided in Table F-2; and the "mit8x8.lo" program with its output results is provided in Table F-3.

Argon Test Data Reduction Step 4.

In Step 4, the error analysis of the test data is performed. The error analysis is discussed in Chapter 5 Section 3.

Argon Test Data Reduction Step 5.

In Step 5, the output results from Step 3 as well at the experimental results obtained in an Argon heat transfer environment are plotted. Using Cricket Graph, the powers and predicted differential temperatures are input into a data file. Each

Table F-1: Lumped k_{eff}/h_{edge} Model Program 3 of 5: "mit8x8.m" with its output results for Argon (15 psig)

Input[1]:

```
(* mit 8x8 file *)

(* evaluate 'gas.m' and 'keff.m' files before this file *)

Fpeak = 1.0;
geom  = box;
La   = 2.0 12.0  0.0254;   (* axial length 2 ft *)
d    = (3.0/8.0) 0.0254;  (* 3/8 in rod diameter *)
pdr  = 1.33;
wpr  = 1.00;
w    = wpr pdr d;
p    = pdr d;
Lc   = 4 ( 8 p );        (* circumferential length *)

Fcond = 2.5;  (* SQ, p/d=1.33, N2 w/c *)
               (* SQ, p/d=1.33, Ar w/c *)
               (* SQ, p/d=1.33, Vac no better than 10 torr *)
(*  Fcond = 2.0;       (* SQ, p/d=1.33, He w/c *)  *)
(*  Fcond = 0.0;       (* SQ, p/d=1.33, Vac better than 1E-5 torr *) *)

(* SQ, p/d=1.33, er = 0.9, Crad = 0.45 *)
(* SQ, p/d=1.33, er = ew = 0.9, Cradw1 = 0.44, Cradw2 = 0.36 *)
Crad   = 0.45;
Cradw1 = 0.44;
Cradw2 = 0.36;


Table[ ΔTkeff[ Ar, Fpeak, Q,
               42.645 + 0.60389 Q - 0.00086181 Q Q + 273,
               La, Lc, d, pdr, wpr, geom,
               Fcond, Crad, Cradw1, Cradw2 ],
               {Q, 1, 300, 20}]
```

Output[1]:

```
{{Ar, 1, 1.127}, {Ar, 21, 20.2658}, {Ar, 41, 34.7773},
 {Ar, 61, 46.331}, {Ar, 81, 55.8747}, {Ar, 101, 64.0003},
 {Ar, 121, 71.1031}, {Ar, 141, 77.4604}, {Ar, 161, 83.2753},
 {Ar, 181, 88.7011}, {Ar, 201, 93.8571}, {Ar, 221, 98.839},
 {Ar, 241, 103.725}, {Ar, 261, 108.581}, {Ar, 281, 113.464},
 {Ar, 301, 118.424}}
```

Table F-2: Lumped k_{eff}/h_{edge} Model Program 4 of 5: "mit8x8.up" with its output results for the Upper Error Bound for Argon (15 psig)

Input[2]:

```
(* mit 8x8 file *)

(* evaluate 'gas.m' and 'keff.m' files before this file *)

Fpeak = 1.0;
geom  = box;
La    = 2.0 12.0 0.0254;  (* axial length 2 ft *)
d     = (3.0/8.0) 0.0254;  (* 3/8 in rod diameter *)
pdr   = 1.33;
wpr   = 1.00;
w     = wpr pdr d;
p     = pdr d;
Lc    = 4 ( 8 p );        (* circumferential length *)

Fcond = 2.5;  (* SQ, p/d=1.33, N2 w/c *)
              (* SQ, p/d=1.33, Ar w/c *)
              (* SQ, p/d=1.33, Vac no better than 10 torr *)
(* Fcond = 2.0;        (* SQ, p/d=1.33, He w/c *)  *)
(* Fcond = 0.0;        (* SQ, p/d=1.33, Vac better than 1E-5 torr *) *)

(* SQ, p/d=1.33, er = 0.8, Crad = 0.39 *)
(* SQ, p/d=1.33, er = ew = 0.8, Cradw1 = 0.37, Cradw2 = 0.30 *)
Crad   = 0.39;
Cradw1 = 0.37;
Cradw2 = 0.30;


Table[ ΔTkeff[ Ar, Fpeak, Q,
          42.645 + 0.60389 Q - 0.00086181 Q Q + 273 - 10,
          La, Lc, d, pdr, wpr, geom,
          Fcond, Crad, Cradw1, Cradw2 ],
          {Q, 1, 300, 20}]
```

Output[2]:

```
{{Ar, 1, 1.35495}, {Ar, 21, 24.0992}, {Ar, 41, 41.0688},
 {Ar, 61, 54.4487}, {Ar, 81, 65.4296}, {Ar, 101, 74.7354},
 {Ar, 121, 82.8405}, {Ar, 141, 90.0734}, {Ar, 161, 96.6714},
 {Ar, 181, 102.812}, {Ar, 201, 108.633}, {Ar, 221, 114.243},
 {Ar, 241, 119.731}, {Ar, 261, 125.171}, {Ar, 281, 130.626},
 {Ar, 301, 136.15}}
```

Table F-3: Lumped k_{eff}/h_{edge} Model Program 5 of 5: "mit8x8.lo" with its output results for the Lower Error Bound for Argon (15 psig)

Input[3]:

```
(* mit 8x8 file *)

(* evaluate 'gas.m' and 'keff.m' files before this file *)

Fpeak = 1.0;
geom  = box;
La    = 2.0 12.0  0.0254;   (* axial length 2 ft *)
d     = (3.0/8.0) 0.0254;   (* 3/8 in rod diameter *)
pdr   = 1.33;
wpr   = 1.00;
w     = wpr pdr d;
p     = pdr d;
Lc    = 4 ( 8 p );           (* circumferential length *)

Fcond = 2.5;  (* SQ, p/d=1.33, N2 w/c *)
              (* SQ, p/d=1.33, Ar w/c *)
              (* SQ, p/d=1.33, Vac no better than 10 torr *)
(*  Fcond = 2.0;       (* SQ, p/d=1.33, He w/c *)  *)
(*  Fcond = 0.0;       (* SQ, p/d=1.33, Vac better than 1E-5 torr *) *)

(* SQ, p/d=1.33, er = 1.0, Crad = 0.51 *)
(* SQ, p/d=1.33, er = ew = 1.0, Cradw1 = 0.52, Cradw2 = 0.41 *)
Crad   = 0.51;
Cradw1 = 0.52;
Cradw2 = 0.41;


Table[ ΔTkeff[ Ar, Fpeak, Q,
       42.645 + 0.60389 Q - 0.00086181 Q Q + 273 + 10,
       La, Lc, d, pdr, wpr, geom,
       Fcond, Crad, Cradw1, Cradw2 ],
       {Q, 1, 300, 20}]
```

Output[3]:

```
{{Ar, 1, 0.947282}, {Ar, 21, 17.2012}, {Ar, 41, 29.7091},
 {Ar, 61, 39.7616}, {Ar, 81, 48.1193}, {Ar, 101, 55.2692},
 {Ar, 121, 61.5422}, {Ar, 141, 67.1741}, {Ar, 161, 72.3391},
 {Ar, 181, 77.1701}, {Ar, 201, 81.7714}, {Ar, 221, 86.2273},
 {Ar, 241, 90.6072}, {Ar, 261, 94.9702}, {Ar, 281, 99.3673},
 {Ar, 301, 103.844}}
```

prediction is then line plotted in the form of Differential Temperature (y-axis) as a function of Power (x-axis) on the same graph. Then a scatter plot of the experimental data is overlaid on the predictions. This graph is presented in Chapter 5 Section 4.

F.2 Above Atmospheric Pressure Helium Data Reduction

This section of Appendix F provides the detailed process of reduction for the Helium data set. The Helium data set includes the data taken above atmospheric pressure with helium as the heat transfer medium (Appendix E.6).

Helium Test Data Reduction Step 1.

In Step 1, the average wall temperature as a function of power is obtained for the Helium data. Using Cricket Graph, the actual power and average wall temperature obtained from the experimental apparatus for Helium are input into a data file. The data is then plotted in the form of Average Wall Temperature (y-axis) as a function of Power (x-axis) and a second order polynomial curve fit of this data provides the function input for Step 3. The plotted Helium data with the curve fit is provided in Figure F-2. The input function for Helium is:

$$y = 31.709 + 0.32574\ x - 2.5663(10)^{-4}\ x^2$$

where x is power and y is the average wall temperature.

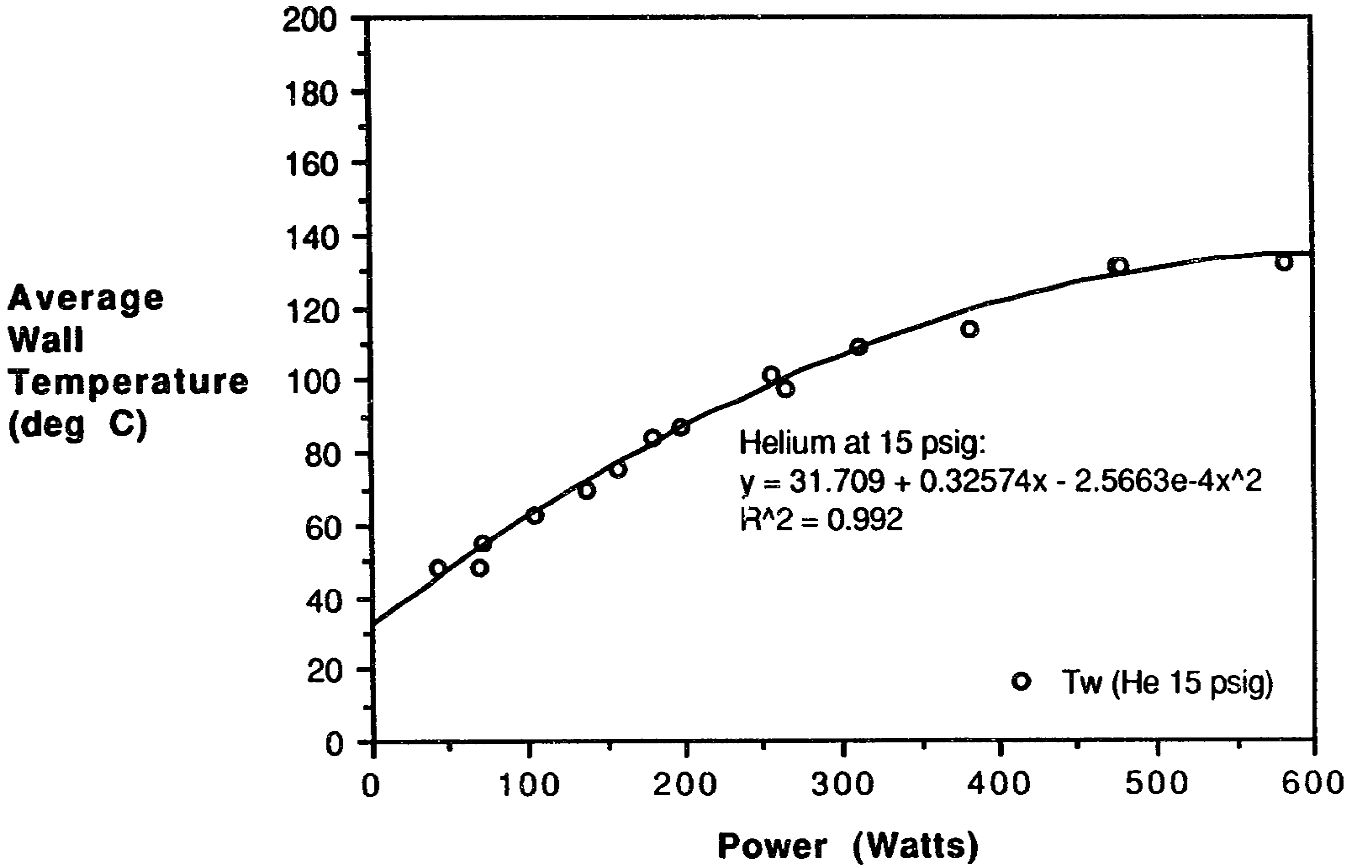


Figure F-2: Average Wall Temperature as a function of Power in Pressurized Helium (15 psig)

Helium Test Data Reduction Step 2.

In Step 2, the Wooten-Epstein relationship only applies to the Air/Nitrogen data set. Go to Step 3.

Helium Test Data Reduction Step 3.

In Step 3, the lumped k_{eff}/h_{edge} model is evaluated to provide a predicted differential temperature between the maximum heater rod temperature and the average wall temperature as a function of power for the Helium test data. Using Mathematica, the function obtained from Step 1 is input into the "mit8x8.m", "mit8x8.up" and "mit8x8.lo" programs in the following format:

31.709 + 0.32574 Q - 0.00025663 Q Q + 273

in the Input Section. Adding 273 converts the experimental temperature units (°C) to the units used in the theoretical prediction calculations (°K). Additionally, the heat transfer medium (He) is input into each "mit8x8" program. The user should also ensure that the appropriate "Fcond" factor is available in each "mit8x8" program. Available means that the appropriate factor is not surrounded by comment characters, "(*" on the left side of "Fcond" for He and a second "*)" at the end of the line. After inputting these items, the lumped k_{eff}/h_{edge} model programs are ready to be executed/evaluated. First execute "gas.m"; second execute "keff.m"; third execute "mit8x8.m"; fourth execute "mit8x8.up"; and lastly execute "mit8x8.lo". The output results from "mit8x8.m", "mit8x8.up" and "mit8x8.lo" are in table form providing the Heat Transfer Medium (N2) in the first column, Power in the second column, and the Predicted Differential Temperature in the third column. Note: $\Delta T(°K) = \Delta T(°C)$. The "mit8x8.m" program with its output results is provided in Table F-4; the "mit8x8.up" program with its output results is provided in Table F-5; and the "mit8x8.lo" program with its output results is provided in Table F-6.

Helium Test Data Reduction Step 4.

In Step 4, the error analysis of the test data is performed. The error analysis is discussed in Chapter 5 Section 3.

Helium Test Data Reduction Step 5.

In Step 5, the output results from Step 3 as well at the experimental results obtained in a Helium heat transfer environment are plotted. Using Cricket Graph, the powers and predicted differential temperatures are input into a data file. Each

Table F-4: Lumped k_{eff}/h_{edge} Model Program 3 of 5: "mit8x8.m" with its output results for Helium (15 psig)

Input[1]:

```
(* mit 8x8 file *)

(* evaluate 'gas.m' and 'keff.m' files before this file *)

Fpeak = 1.0;
geom  = box;
La    = 2.0 12.0  0.0254;   (* axial length 2 ft *)
d     = (3.0/8.0) 0.0254;  (* 3/8 in rod diameter *)
pdr   = 1.33;
wpr   = 1.00;
w     = wpr pdr d;
p     = pdr d;
Lc    = 4 ( 8 p );          (* circumferential length *)

(*  Fcond = 2.5;         (* SQ, p/d=1.33, N2 w/c *)
                         (* SQ, p/d=1.33, Ar w/c *)
                         (* SQ, p/d=1.33, Vac no better than 10 torr *)   *)
Fcond = 2.0;  (* SQ, p/d=1.33, He w/c *)
(*  Fcond = 0.0,         (* SQ, p/d=1.33, Vac better than 1E-5 torr *) *)

(* SQ, p/d=1.33, er = 0.9, Crad = 0.45 *)
(* SQ, p/d=1.33, er = ew = 0.9, Cradw1 = 0.44, Cradw2 = 0.36 *)
Crad   = 0.45;
Cradw1 = 0.44;
Cradw2 = 0.36;


Table[ ΔTkeff[ He, Fpeak, Q,
            31.709 + 0.32574 Q - 0.00025663 Q Q + 273,
            La, Lc, d, pdr, wpr, geom,
            Fcond, Crad, Cradw1, Cradw2 ],
            {Q, 1, 600, 20}]
```

Output[1]:

```
{{He, 1, 0.43052}, {He, 21, 8.67316}, {He, 41, 16.2794},
 {He, 61, 23.331}, {He, 81, 29.8967}, {He, 101, 36.0349},
 {He, 121, 41.7961}, {He, 141, 47.224}, {He, 161, 52.3569},
 {He, 181, 57.2284}, {He, 201, 61.8685}, {He, 221, 66.3038},
 {He, 241, 70.558}, {He, 261, 74.6525}, {He, 281, 78.6068},
 {He, 301, 82.4384}, {He, 321, 86.1633}, {He, 341, 89.796},
 {He, 361, 93.3499}, {He, 381, 96.8376}, {He, 401, 100.27},
 {He, 421, 103.659}, {He, 441, 107.013}, {He, 461, 110.342},
 {He, 481, 113.654}, {He, 501, 116.958}, {He, 521, 120.262},
 {He, 541, 123.573}, {He, 561, 126.897}, {He, 581, 130.243},
 {He, 601, 133.616}}
```

Table F-5: Lumped k_{eff}/h_{edge} Model Program 4 of 5: "mit8x8.up" with its output results for the Upper Error Bound for Helium (15 psig)

Input[2]:

```
(* mit 8x8 file *)

(* evaluate 'gas.m' and 'keff.m' files before this file *)

Fpeak = 1.0;
geom  = box;
La    = 2.0 12.0  0.0254;   (* axial length 2 ft *)
d     = (3.0/8.0) 0.0254;   (* 3/8 in rod diameter *)
pdr   = 1.33;
wpr   = 1.00;
w     = wpr pdr d;
p     = pdr d;
Lc    = 4 ( 8 p );          (* circumferential length *)

(*  Fcond = 2.5;           (* SQ, p/d=1.33, N2 w/c *)
                           (* SQ, p/d=1.33, Ar w/c *)
                           (* SQ, p/d=1.33, Vac no better than 10 torr *)  *)
Fcond = 2.0;  (* SQ, p/d=1.33, He w/c *)
(*  Fcond = 0.0,           (* SQ, p/d=1.33, Vac better than 1E-5 torr *) *)

(* SQ, p/d=1.33, er = 0.8, Crad = 0.39 *)
(* SQ, p/d=1.33, er = ew = 0.8, Cradw1 = 0.37, Cradw2 = 0.30 *)
Crad   = 0.39;
Cradw1 = 0.37;
Cradw2 = 0.30;


Table[ ΔTkeff[ He, Fpeak, Q,
              31.709 + 0.32574 Q - 0.00025663 Q Q + 273 - 10,
              La, Lc, d, pdr, wpr, geom,
              Fcond, Crad, Cradw1, Cradw2 ],
              {Q, 1, 600, 20}]
```

Output[2]:

```
{{He, 1, 0.463941}, {He, 21, 9.35412}, {He, 41, 17.5723},
 {He, 61, 25.2051}, {He, 81, 32.3247}, {He, 101, 38.9923},
 {He, 121, 45.2607}, {He, 141, 51.1754}, {He, 161, 56.7764},
 {He, 181, 62.0987}, {He, 201, 67.1735}, {He, 221, 72.0286},
 {He, 241, 76.6889}, {He, 261, 81.1769}, {He, 281, 85.5127},
 {He, 301, 89.7148}, {He, 321, 93.8001}, {He, 341, 97.7838},
 {He, 361, 101.68}, {He, 381, 105.502}, {He, 401, 109.262},
 {He, 421, 112.97}, {He, 441, 116.638}, {He, 461, 120.275},
 {He, 481, 123.89}, {He, 501, 127.493}, {He, 521, 131.09},
 {He, 541, 134.69}, {He, 561, 138.3}, {He, 581, 141.928},
 {He, 601, 145.58}}
```

Table F-6: Lumped k_{eff}/h_{edge} Model Program 5 of 5: "mit8x8.lo" with its output results for the Lower Error Bound for Helium (15 psig)

Input[3]:

```
(* mit 8x8 file *)

(* evaluate 'gas.m' and 'keff.m' files before this file *)

Fpeak = 1.0;
geom = box;
La   = 2.0 12.0  0.0254;   (* axial length 2 ft *)
d    = (3.0/8.0) 0.0254;  (* 3/8 in rod diameter *)
pdr  = 1.33;
wpr  = 1.00;
w    = wpr pdr d;
p    = pdr d;
Lc   = 4 ( 8 p );         (* circumferential length *)

(*  Fcond = 2.5;          (* SQ, p/d=1.33, N2 w/c *)
                          (* SQ, p/d=1.33, Ar w/c *)
                          (* SQ, p/d=1.33, Vac no better than 10 torr *)  *)
Fcond = 2.0;  (* SQ, p/d=1.33, He w/c *)
(*  Fcond = 0.0,          (* SQ, p/d=1.33, Vac better than 1E-5 torr *) *)

(* SQ, p/d=1.33, er = 1.0, Crad = 0.51 *)
(* SQ, p/d=1.33, er = ew = 1.0, Cradw1 = 0.52, Cradw2 = 0.41 *)
Crad   = 0.51;
Cradw1 = 0.52;
Cradw2 = 0.41;


Table[ ΔTkeff[ He, Fpeak, Q,
            31.709 + 0.32574 Q - 0.00025663 Q Q + 273 + 10,
            La, Lc, d, pdr, wpr, geom,
            Fcond, Crad, Cradw1, Cradw2 ],
            {Q, 1, 600, 20}]
```

Output[3]:

```
{ {He, 1, 0.398796}, {He, 21, 8.02891}, {He, 41, 15.0604},
  {He, 61, 21.5702}, {He, 81, 27.6232}, {He, 101, 33.2748},
  {He, 121, 38.573}, {He, 141, 43.5591}, {He, 161, 48.2697},
  {He, 181, 52.7366}, {He, 201, 56.9884}, {He, 221, 61.05},
  {He, 241, 64.9443}, {He, 261, 68.6913}, {He, 281, 72.3095},
  {He, 301, 75.8153}, {He, 321, 79.224}, {He, 341, 82.5491},
  {He, 361, 85.8035}, {He, 381, 88.9987}, {He, 401, 92.1456},
  {He, 421, 95.2541}, {He, 441, 98.3337}, {He, 461, 101.393},
  {He, 481, 104.44}, {He, 501, 107.483}, {He, 521, 110.529},
  {He, 541, 113.585}, {He, 561, 116.658}, {He, 581, 119.754},
  {He, 601, 122.88}}
```

prediction is then line plotted in the form of Differential Temperature (y-axis) as a function of Power (x-axis) on the same graph. Then a scatter plot of the experimental data is overlaid on the predictions. This graph is presented in Chapter 5 Section 4.

F.3 Below Atmospheric Pressure Data Reduction

This section of Appendix F provides the detailed process of reduction for the Below Atmospheric Pressure data set. This data set includes the data taken below atmospheric pressure with air as the initial heat transfer medium (Appendix E.7).

Below Atmospheric Pressure Test Data Reduction Step 1.

In Step 1, the average wall temperature as a function of power is obtained for the Below Atmospheric Pressure data. Using Cricket Graph, the actual power and average wall temperature obtained from the experimental apparatus for Below Atmospheric Pressure are input into a data file. The data is then plotted in the form of Average Wall Temperature (y-axis) as a function of Power (x-axis) and a second order polynomial curve fit of this data provides the function input for Step 3. The plotted Below Atmospheric Pressure data with the curve fit is provided in Figure F-3. The input function for Below Atmospheric Pressure is:

$$y = 55.157 + 1.4479\,x - 4.6105(10)^{-3}\,x^2$$

where x is power and y is the average wall temperature.

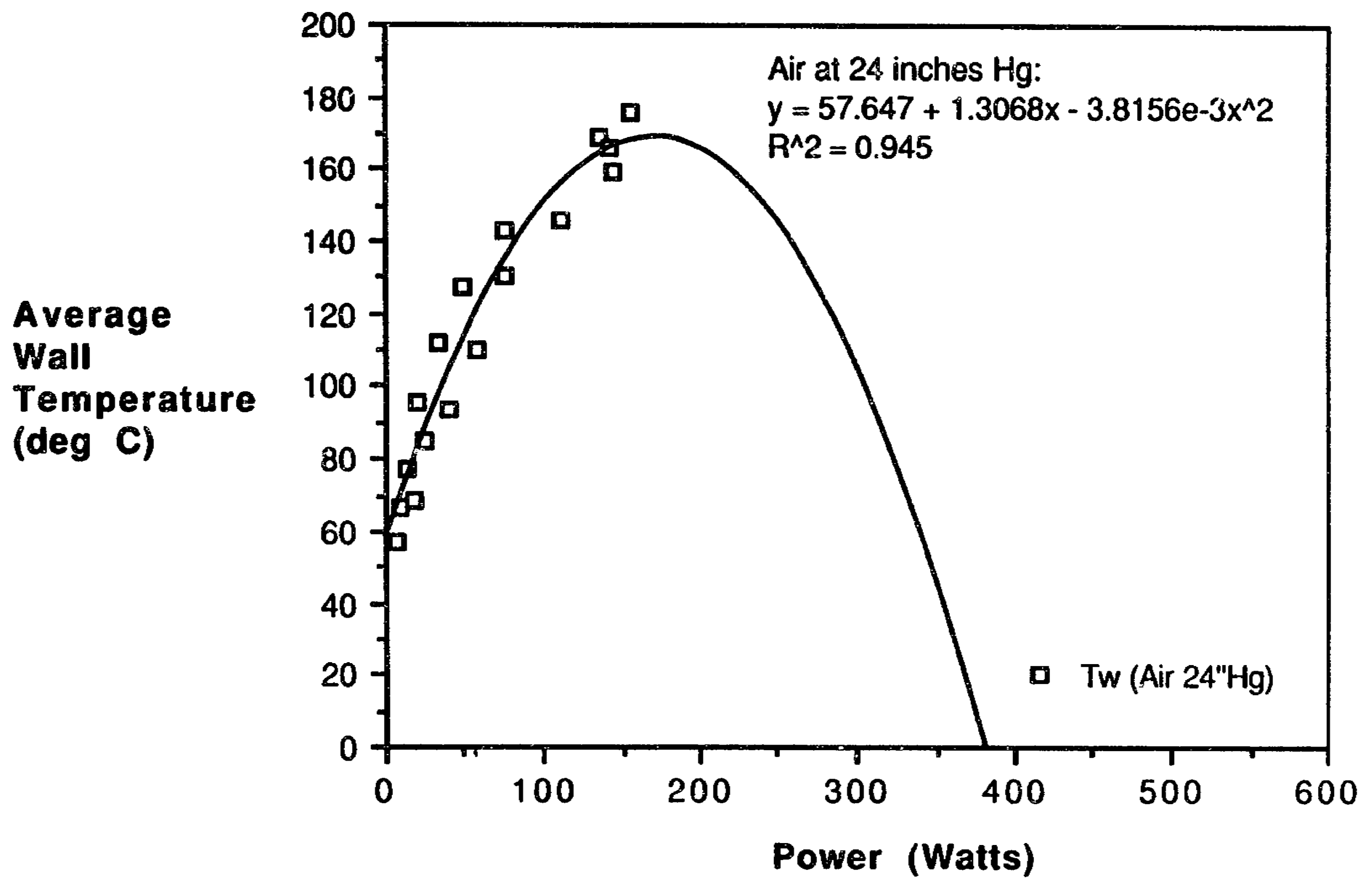


Figure F-3: Average Wall Temperature as a function of Power at Below Atmospheric Pressure with Air as the Initial Fill Gas (24 inches Hg)

Below Atmospheric Pressure Test Data Reduction Step 2.

In Step 2, the Wooten-Epstein relationship only applies to the Air/Nitrogen data set. Go to Step 3.

Below Atmospheric Pressure Test Data Reduction Step 3.

In Step 3, the lumped k_{eff}/h_{edge} model is evaluated to provide a predicted differential temperature between the maximum heater rod temperature and the average wall temperature as a function of power for the Below Atmospheric Pressure test data. Using Mathematica, the function obtained from Step 1 is input into the "mit8x8.m", "mit8x8.up" and "mit8x8.lo" programs in the following format:

55.157 + 1.4479 Q - 0.0046105 Q Q + 273

in the Input Section. Adding 273 converts the experimental temperature units (°C) to the units used in the theoretical prediction calculations (°K). Additionally, the heat transfer medium (Vac) is input into each "mit8x8" program. The user should also ensure that the appropriate "Fcond" factor is available in each "mit8x8" program. Available means that the appropriate factor is not surrounded by comment characters, "(*" on the left side of "Fcond" for Vac (24"Hg) and a second "*)" at the end of the line. After inputting these items, the lumped k_{eff}/h_{edge} model programs are ready to be executed/evaluated. First execute "gas.m"; second execute "keff.m"; third execute "mit8x8.m"; fourth execute "mit8x8.up"; and lastly execute "mit8x8.lo". The output results from "mit8x8.m", "mit8x8.up" and "mit8x8.lo" are in table form providing the Heat Transfer Medium (Vac) in the first column, Power in the second column, and the Predicted Differential Temperature in the third column. Note: $\Delta T(°K) = \Delta T(°C)$. The "mit8x8.m" program with its output results is provided in Table F-7; the "mit8x8.up" program with its output results is provided in Table F-8; and the "mit8x8.lo" program with its output results is provided in Table F-9.

Below Atmospheric Pressure Test Data Reduction Step 4.

In Step 4, the error analysis of the test data is performed. The error analysis is discussed in Chapter 5 Section 3.

Below Atmospheric Pressure Test Data Reduction Step 5.

In Step 5, the output results from Step 3 as well at the experimental results obtained in a Below Atmospheric Pressure heat transfer environment are plotted. Using Cricket Graph, the powers and predicted differential temperatures are input into a data

Table F-7: Lumped k_{eff}/h_{edge} Model Program 3 of 5: "mit8x8.m" with its output results for Below Atmospheric Pressure (24 inches Hg)

Input[1]:

```
(* mit 8x8 file *)

(* evaluate 'gas.m' and 'keff.m' files before this file *)

Fpeak = 1.0;
geom  = box;
La    = 2.0 12.0  0.0254;   (* axial length 2 ft *)
d     = (3.0/8.0) 0.0254;   (* 3/8 in rod diameter *)
pdr   = 1.33;
wpr   = 1.00;
w     = wpr pdr d;
p     = pdr d;
Lc    = 4 ( 8 p );          (* circumferential length *)

Fcond = 2.5;  (* SQ, p/d=1.33, N2 w/c *)
              (* SQ, p/d=1.33, Ar w/c *)
              (* SQ, p/d=1.33, Vac no better than 10 torr *)
(*  Fcond = 2.0;      (* SQ, p/d=1.33, He w/c *)  *)
(*  Fcond = 0.0;      (* SQ, p/d=1.33, Vac better than 1E-5 torr *) *)

(* SQ, p/d=1.33, er = 0.9, Crad = 0.45 *)
(* SQ, p/d=1.33, er = ew = 0.9, Cradw1 = 0.44, Cradw2 = 0.36 *)
Crad   = 0.45;
Cradw1 = 0.44;
Cradw2 = 0.36;


Table[ ΔTkeff[ Vac, Fpeak, Q,
            57.647 + 1.3068 Q - 0.0038156 Q Q + 273,
            La, Lc, d, pdr, wpr, geom,
            Fcond, Crad, Cradw1, Cradw2 ],
            {Q, 1, 200, 20}]
```

Output[1]:

```
{{Vac, 1, 0.895672}, {Vac, 21, 15.2798}, {Vac, 41, 25.2743},
 {Vac, 61, 32.8867}, {Vac, 81, 39.1919},
 {Vac, 101, 44.8369}, {Vac, 121, 50.2521},
 {Vac, 141, 55.7551}, {Vac, 161, 61.6061},
 {Vac, 181, 68.0418}, {Vac, 201, 75.2972}}
```

Table F-8: Lumped k_{eff}/h_{edge} Model Program 4 of 5: "mit8x8.up" with its output results for the Upper Error Bound for Below Atmospheric Pressure (24 inches Hg)

Input[2]:

```
(* mit 8x8 file *)

(* evaluate 'gas.m' and 'keff.m' files before this file *)

Fpeak = 1.0;
geom  = box;
La    = 2.0 12.0  0.0254;   (* axial length 2 ft *)
d     = (3.0/8.0) 0.0254;   (* 3/8 in rod diameter *)
pdr   = 1.33;
wpr   = 1.00;
w     = wpr pdr d;
p     = pdr d;
Lc    = 4 ( 8 p );          (* circumferential length *)

Fcond = 2.5;   (* SQ, p/d=1.33, N2 w/c *)
               (* SQ, p/d=1.33, Ar w/c *)
               (* SQ, p/d=1.33, Vac no better than 10 torr *)
(*  Fcond = 2.0;       (* SQ, p/d=1.33, He w/c *)  *)
(*  Fcond = 0.0;       (* SQ, p/d=1.33, Vac better than 1E-5 torr *) *)

(* SQ, p/d=1.33, er = 0.8, Crad = 0.39 *)
(* SQ, p/d=1.33, er = ew = 0.8, Cradw1 = 0.37, Cradw2 = 0.30 *)
Crad   = 0.39;
Cradw1 = 0.37;
Cradw2 = 0.30;


Table[ ΔTkeff[ Vac, Fpeak, Q,
          57.647 + 1.3068 Q - 0.0038156 Q Q + 273 - 10,
          La, Lc, d, pdr, wpr, geom,
          Fcond, Crad, Cradw1, Cradw2 ],
          {Q, 1, 200, 20}]
```

Output[2]:

```
{{Vac, 1, 1.05915}, {Vac, 21, 17.9934}, {Vac, 41, 29.6939},
 {Vac, 61, 38.577}, {Vac, 81, 45.9137}, {Vac, 101, 52.4602},
 {Vac, 121, 58.7153}, {Vac, 141, 65.0425},
 {Vac, 161, 71.7353}, {Vac, 181, 79.0558},
 {Vac, 201, 87.2589}}
```

Table F-9: Lumped k_{eff}/h_{edge} Model Program 5 of 5: "mit8x8.lo" with its output results for the Lower Error Bound for Below Atmospheric Pressure (24 inches Hg)

Input[3]:

```
(* mit 8x8 file *)

(* evaluate 'gas.m' and 'keff.m' files before this file *)

Fpeak = 1.0;
geom  = box;
La    = 2.0 12.0  0.0254;   (* axial length 2 ft *)
d     = (3.0/8.0) 0.0254;   (* 3/8 in rod diameter *)
pdr   = 1.33;
wpr   = 1.00;
w     = wpr pdr d;
p     = pdr d;
Lc    = 4 ( 8 p );          (* circumferential length *)

Fcond = 2.5;  (* SQ, p/d=1.33, N2 w/c *)
              (* SQ, p/d=1.33, Ar w/c *)
              (* SQ, p/d=1.33, Vac no better than 10 torr *)
(*  Fcond = 2.0;      (* SQ, p/d=1.33, He w/c *)   *)
(*  Fcond = 0.0;      (* SQ, p/d=1.33, Vac better than 1E-5 torr *) *)

(* SQ, p/d=1.33, er = 1.0, Crad = 0.51 *)
(* SQ, p/d=1.33, er = ew = 1.0, Cradw1 = 0.52, Cradw2 = 0.41 *)
Crad   = 0.51;
Cradw1 = 0.52;
Cradw2 = 0.41;


Table[ ΔTkeff[ Vac, Fpeak, Q,
        57.647 + 1.3068 Q - 0.0038156 Q Q + 273 + 10,
        La, Lc, d, pdr, wpr, geom,
        Fcond, Crad, Cradw1, Cradw2 ],
        {Q, 1, 200, 20}]
```

Output[3]:

```
{{Vac, 1, 0.763783}, {Vac, 21, 13.0892}, {Vac, 41, 21.7098},
 {Vac, 61, 28.3027}, {Vac, 81, 33.7813},
 {Vac, 101, 38.7016}, {Vac, 121, 43.4374},
 {Vac, 141, 48.2674}, {Vac, 161, 53.423},
 {Vac, 181, 59.118}, {Vac, 201, 65.5688}}
```

file. Each prediction is then line plotted in the form of Differential Temperature (y-axis) as a function of Power (x-axis) on the same graph. Then a scatter plot of the experimental data is overlaid on the predictions. This graph is presented in Chapter 5 Section 4.

APPENDIX G

CODE FOR CORRECTING DATA TO ACCOUNT FOR END LOSSES

This appendix contains the computer code written by R. Manteufel to determine heat loss from the rod bundle out the ends on the experimental apparatus. The computer code is written for the Apple Macintosh software, Mathematica.

Input[1]:

```
ClearAll[Qloss];
Qloss[ dt11_, dt27_, dt55_, dt73_] := (
        k  = 400.0  ;  (*copper *)
        d  = 3/8          0.0254;
        dt = 0.049        0.0254;
        L  = 1   12       0.0254;
        dtring1 = dt11;
        dtring2 = ( dt27 + dt73 )/2;
        dtring3 = ( dt27 + dt73 + dt55 )/3;
        dtring4 = ( dt55 );
          2 N[Pi]  d  dt  k  /  L  (28 dtring1 +
                                   20 dtring2 +
                                   12 dtring3 +
                                    4 dtring4 ))

{{40.5, Qloss[ 0.03, 1.95, 3.42, 1.69 ]},
 {69.4, Qloss[ 0.09, 2.96, 5.04, 2.42 ]},
 {106., Qloss[ 0.40, 4.00, 7.00, 3.40 ]},
 {85.1, Qloss[ 0.80, 4.50, 7.40, 4.50 ]},
 {150., Qloss[ 0.70, 5.00, 8.40, 4.60 ]},
 {187., Qloss[ 1.00, 6.20, 10.5, 5.70 ]},
 {160., Qloss[ 1.30, 6.80, 11.6, 6.60 ]},
 {243., Qloss[ 1.20, 7.50, 12.9, 7.20 ]},
 {266., Qloss[ 1.80, 9.00, 15.4, 8.90 ]},
 {292., Qloss[ 2.10, 10.1, 15.0, 10.9 ]},
 {316., Qloss[ 1.90, 9.80, 16.2, 10.0 ]},
 {359., Qloss[ 2.00, 10.5, 17.7, 10.8 ]},
 {389., Qloss[ 2.30, 10.6, 17.8, 10.7 ]},
 {31.8, Qloss[ 0.21, 1.81, 2.97, 1.53 ]},
 {64.0, Qloss[ 0.45, 3.01, 4.99, 2.61 ]},
 {144., Qloss[ 1.00, 5.10, 8.20, 4.70 ]},
 {147., Qloss[ 1.00, 5.20, 8.80, 4.80 ]},
 {210., Qloss[ 1.50, 7.60, 12.9, 7.30 ]},
 {26.0, Qloss[ 0.40, 2.09, 2.85, 1.54 ]},
 {42.5, Qloss[ 0.80, 2.79, 3.96, 2.10 ]},
 {55.9, Qloss[ 0.70, 3.49, 4.93, 2.59 ]},
 {102., Qloss[ 1.20, 4.70, 6.60, 3.60 ]},
 {164., Qloss[ 1.30, 5.70, 8.20, 4.70 ]},
 {216., Qloss[ 1.70, 7.10, 11.0, 6.10 ]},
 {272., Qloss[ 2.10, 8.60, 12.6, 7.30 ]},
 {381., Qloss[ 2.80, 10.4, 15.4, 9.20 ]},
 {390., Qloss[ 3.20, 12.0, 18.1, 10.8 ]},
 {19.3, Qloss[ 0.35, 2.00, 2.98, 1.70 ]},
 {63.8, Qloss[ 0.90, 4.20, 6.20, 3.56 ]},
 {104., Qloss[ 1.10, 5.40, 7.70, 4.70 ]},
 {165., Qloss[ 1.80, 6.60, 9.70, 6.10 ]},
 {232., Qloss[ 2.00, 8.20, 11.9, 7.20 ]},
 {305., Qloss[ 3.00, 10.4, 15.5, 9.40 ]},
 {356., Qloss[ 3.10, 11.5, 17.0, 10.5 ]},
```

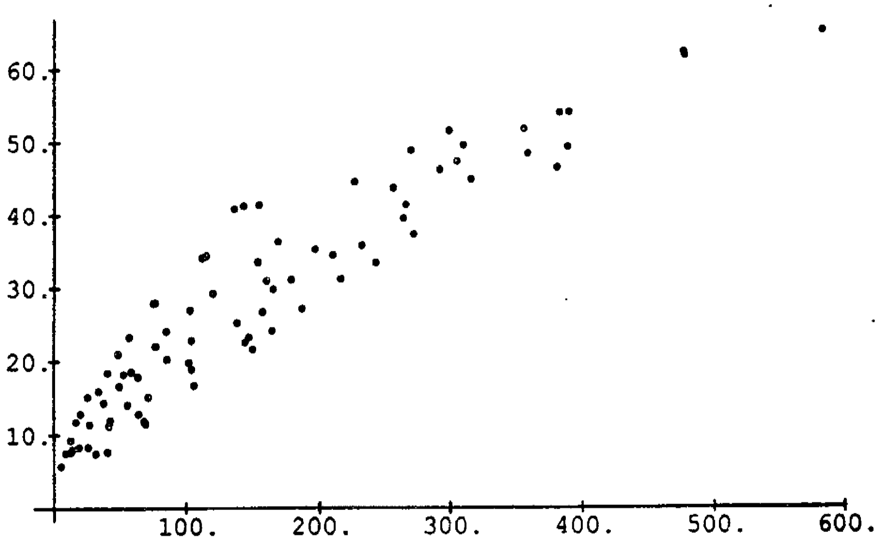
```
{41.7, Qloss[ 0.34, 2.57, 3.84, 2.76 ]},
{71.6, Qloss[ 0.48, 3.39, 5.17, 3.75 ]},
{104., Qloss[ 0.71, 4.24, 6.10, 4.71 ]},
{157., Qloss[ 1.18, 5.80, 8.60, 6.50 ]},
{197., Qloss[ 1.90, 7.40, 10.9, 8.40 ]},
{256., Qloss[ 2.50, 9.10, 13.5, 10.2 ]},
{383., Qloss[ 3.10, 11.1, 16.6, 12.7 ]},
{478., Qloss[ 3.50, 12.8, 18.9, 14.6 ]},
{477., Qloss[ 3.60, 12.9, 18.9, 14.6 ]},
{68.1, Qloss[ 0.57, 2.51, 3.86, 2.83 ]},
{138., Qloss[ 1.26, 5.34, 8.10, 5.98 ]},
{179., Qloss[ 1.60, 6.60, 9.60, 7.50 ]},
{264., Qloss[ 2.30, 8.20, 12.0, 9.30 ]},
{310., Qloss[ 2.90, 10.2, 15.2, 11.6 ]},
{583., Qloss[ 3.60, 13.5, 19.9, 15.6 ]},
{13.4, Qloss[ 0.40, 1.82, 2.74, 1.46 ]},
{26.8, Qloss[ 0.59, 2.53, 3.96, 2.34 ]},
{37.6, Qloss[ 0.70, 3.22, 5.27, 2.85 ]},
{53.0, Qloss[ 1.00, 4.30, 6.20, 3.50 ]},
{59.0, Qloss[ 0.80, 4.10, 6.60, 4.10 ]},
{85.0, Qloss[ 1.20, 5.30, 8.20, 5.20 ]},
{120., Qloss[ 1.40, 6.50, 10.2, 6.30 ]},
{169., Qloss[ 2.00, 7.90, 12.6, 7.50 ]},
{227., Qloss[ 2.60, 9.50, 15.2, 9.20 ]},
{299., Qloss[ 2.80, 11.1, 17.8, 10.8 ]},
{14.1, Qloss[ 0.39, 1.90, 2.83, 1.59 ]},
{49.6, Qloss[ 0.80, 3.80, 5.80, 3.42 ]},
{76.9, Qloss[ 1.00, 4.90, 7.60, 4.90 ]},
{103., Qloss[ 1.30, 6.00, 9.30, 5.80 ]},
{154., Qloss[ 1.60, 7.40, 11.8, 7.20 ]},
{270., Qloss[ 2.90, 10.4, 16.5, 10.1 ]},
{5.56, Qloss[ 0.13, 1.11, 2.06, 1.63 ]},
{8.99, Qloss[ 0.15, 1.49, 2.70, 2.15 ]},
{12.7, Qloss[ 0.17, 1.79, 3.50, 2.64 ]},
{20.0, Qloss[ 0.30, 2.50, 4.70, 3.60 ]},
{33.7, Qloss[ 0.30, 3.20, 5.90, 4.50 ]},
{48.5, Qloss[ 0.50, 4.30, 7.80, 5.60 ]},
{76.5, Qloss[ 0.90, 5.60, 10.1, 7.30 ]},
{115., Qloss[ 1.20, 7.00, 12.2, 8.80 ]},
{155., Qloss[ 1.50, 8.50, 14.5, 10.5 ]},
{16.8, Qloss[ 0.12, 2.45, 4.40, 3.42 ]},
{25.5, Qloss[ 0.20, 3.20, 5.40, 4.40 ]},
{40.6, Qloss[ 0.40, 3.80, 6.40, 5.20 ]},
{57.5, Qloss[ 0.60, 4.70, 8.40, 6.30 ]},
{75.4, Qloss[ 0.80, 5.70, 10.0, 7.40 ]},
{112., Qloss[ 1.00, 6.90, 12.2, 9.10 ]},
{136., Qloss[ 1.80, 8.00, 13.8, 10.4 ]},
{143., Qloss[ 1.80, 8.20, 13.8, 10.5 ]} }
```

Output[1]:
{{40.5, 7.73794}, {69.4, 11.5502}, {106., 16.6958}, {85.1, 20.293}, {150., 21.6224}, {187., 27.2333}, {160., 30.9674}, {243., 33.4894}, {266., 41.4658}, {292., 46.2165}, {316., 44.9653}, {359., 48.4648}, {389., 49.3641}, {31.8, 7.46815}, {64., 12.8249}, {144., 22.5609}, {147., 23.3038}, {210., 34.5842}, {26., 8.29121}, {42.5, 11.9784}, {55.9, 14.0917}, {102., 19.8043}, {164., 24.2031}, {216., 31.3193}, {272., 37.3603}, {381., 46.5293}, {390., 54.1148}, {19.3, 8.35182}, {63.8, 17.9314}, {104., 22.8541}, {165., 29.8922}, {232., 35.8549}, {305., 47.4286}, {356., 51.886}, {41.7, 11.2276}, {71.6, 15.1279}, {104., 18.9617}, {157., 26.7876}, {197., 35.3466}, {256., 43.8118}, {383., 54.0366}, {478., 61.8566}, {477., 62.2672}, {68.1, 11.8865}, {138., 25.2744}, {179., 31.1825}, {264., 39.6281}, {310., 49.6573}, {583., 65.2388}, {13.4, 7.72621}, {26.8, 11.3762}, {37.6, 14.3439}, {53., 18.2598}, {59., 18.5726}, {85., 24.0662}, {120., 29.3252}, {169., 36.4023}, {227., 44.5938}, {299., 51.5537}, {14.1, 8.05661}, {49.6, 16.6059}, {76.9, 22.0916}, {103., 26.9792}, {154., 33.5871}, {270., 48.8949}, {5.56, 5.71646}, {8.99, 7.50334}, {12.7, 9.26481}, {20., 12.8444}, {33.7, 15.9725}, {48.5, 21.0164}, {76.5, 28.0153}, {115., 34.4473}, {155., 41.4463}, {16.8, 11.8024}, {25.5, 15.1709}, {40.6, 18.4162}, {57.5, 23.2647}, {75.4, 27.9371}, {112., 34.1736}, {136., 40.8989}, {143., 41.3094}}

Input[2]:

```
lp = ListPlot[ {{40.5, 7.73794}, {69.4, 11.5502}, {106., 16.6958},
   {85.1, 20.293}, {150., 21.6224}, {187., 27.2333},
   {160., 30.9674}, {243., 33.4894}, {266., 41.4658},
   {292., 46.2165}, {316., 44.9653}, {359., 48.4648},
   {389., 49.3641}, {31.8, 7.46815}, {64., 12.8249},
   {144., 22.5609}, {147., 23.3038}, {210., 34.5842},
   {26., 8.29121}, {42.5, 11.9784}, {55.9, 14.0917},
   {102., 19.8043}, {164., 24.2031}, {216., 31.3193},
   {272., 37.3603}, {381., 46.5293}, {390., 54.1148},
   {19.3, 8.35182}, {63.8, 17.9314}, {104., 22.8541},
   {165., 29.8922}, {232., 35.8549}, {305., 47.4286},
   {356., 51.886}, {41.7, 11.2276}, {71.6, 15.1279},
   {104., 18.9617}, {157., 26.7876}, {197., 35.3466},
   {256., 43.8118}, {383., 54.0366}, {478., 61.8566},
   {477., 62.2672}, {68.1, 11.8865}, {138., 25.2744},
   {179., 31.1825}, {264., 39.6281}, {310., 49.6573},
   {583., 65.2388}, {13.4, 7.72621}, {26.8, 11.3762},
   {37.6, 14.3439}, {53., 18.2598}, {59., 18.5726},
   {85., 24.0662}, {120., 29.3252}, {169., 36.4023},
   {227., 44.5938}, {299., 51.5537}, {14.1, 8.05661},
   {49.6, 16.6059}, {76.9, 22.0916}, {103., 26.9792},
   {154., 33.5871}, {270., 48.8949}, {5.56, 5.71646},
   {8.99, 7.50334}, {12.7, 9.26481}, {20., 12.8444},
   {33.7, 15.9725}, {48.5, 21.0164}, {76.5, 28.0153},
   {115., 34.4473}, {155., 41.4463}, {16.8, 11.8024},
   {25.5, 15.1709}, {40.6, 18.4162}, {57.5, 23.2647},
   {75.4, 27.9371}, {112., 34.1736}, {136., 40.8989},
   {143., 41.3094}} ]
```

Output[2]:



Input[3]:

```
fti = Fit [{{40.5, 7.73794}, {69.4, 11.5502}, {106., 16.6958},
  {85.1, 20.293}, {150., 21.6224}, {187., 27.2333},
  {160., 30.9674}, {243., 33.4894}, {266., 41.4658},
  {292., 46.2165}, {316., 44.9653}, {359., 48.4648},
  {389., 49.3641}, {31.8, 7.46815}, {64., 12.8249},
  {144., 22.5609}, {147., 23.3038}, {210., 34.5842},
  {26., 8.29121}, {42.5, 11.9784}, {55.9, 14.0917},
  {102., 19.8043}, {164., 24.2031}, {216., 31.3193},
  {272., 37.3603}, {381., 46.5293}, {390., 54.1148},
  {19.3, 8.35182}, {63.8, 17.9314}, {104., 22.8541},
  {165., 29.8922}, {232., 35.8549}, {305., 47.4286},
  {356., 51.886}, {41.7, 11.2276}, {71.6, 15.1279},
  {104., 18.9617}, {157., 26.7876}, {197., 35.3466},
  {256., 43.8118}, {383., 54.0366}, {478., 61.8566},
  {477., 62.2672}, {68.1, 11.8865}, {138., 25.2744},
  {179., 31.1825}, {264., 39.6281}, {310., 49.6573},
  {583., 65.2388}, {13.4, 7.72621}, {26.8, 11.3762},
  {37.6, 14.3439}, {53., 18.2598}, {59., 18.5726},
  {85., 24.0662}, {120., 29.3252}, {169., 36.4023},
  {227., 44.5938}, {299., 51.5537}, {14.1, 8.05661},
  {49.6, 16.6059}, {76.9, 22.0916}, {103., 26.9792},
  {154., 33.5871}, {270., 48.8949}, {5.56, 5.71646},
  {8.99, 7.50334}, {12.7, 9.26481}, {20., 12.8444},
  {33.7, 15.9725}, {48.5, 21.0164}, {76.5, 28.0153},
  {115., 34.4473}, {155., 41.4463}, {16.8, 11.8024},
  {25.5, 15.1709}, {40.6, 18.4162}, {57.5, 23.2647},
  {75.4, 27.9371}, {112., 34.1736}, {136., 40.8989},
  {143., 41.3094}} , {1,q}, q]
```

Output[3]:

11.0376 + 0.111129*q