TECHNICAL SUPPORT FOR GEIS:
RADIOACTIVE WASTE ISOLATION
IN GEOLOGIC FORMATIONS

Volume 20

Thermomechanical Stress Analysis
and Development of Thermal Loading Guidelines

April 1978

MASTER

Prepared By

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UNION
CARBIDE

OFFICE OF WASTE ISOLATION
OAK RIDGE, TENNESSEE

*prepared for the U.S. DEPARTMENT OF ENERGY under
U.S. GOVERNMENT Contract W-7405 eng 26*

*This report was prepared by Dames & Moore under
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Y/OWI/TM-36/20

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Volume No.	Volume Title	Prepared by*
TM-36/1	Executive Summary	SAI
TM-36/2	Commercial Waste Forms, Packaging and Projections for Preconceptual Repository Design Studies	SAI
TM-36/3	Stratigraphies of Salt, Granite, Shale and Basalt	D&M
TM-36/4	Baseline Rock Properties-Salt	D&M
TM-36/5	Baseline Rock Properties-Granite	D&M
TM-36/6	Baseline Rock Properties-Shale	D&M
TM-36/7	Baseline Rock Properties-Basalt	D&M
TM-36/8	Repository Preconceptual Design Studies: Salt	PBQD
TM-36/9	Drawings for Repository Preconceptual Design Studies: Salt	PBQD
TM-36/10	Repository Preconceptual Design Studies: Granite	PBQD
TM-36/11	Drawings for Repository Preconceptual Design Studies: Granite	PBQD
TM-36/12	Repository Preconceptual Design Studies: Shale	PBQD
TM-36/13	Drawings for Repository Preconceptual Design Studies: Shale	PBQD
TM-36/14	Repository Preconceptual Design Studies: Basalt	PBQD
TM-36/15	Drawings for Repository Preconceptual Design Studies: Basalt	PBQD
TM-36/16	Repository Preconceptual Design Studies: BPNL Waste Forms in Salt	PBQD
TM-36/17	Drawings for Repository Preconceptual Design Studies: BPNL Waste Forms in Salt	PBQD
TM-36/18	Facility Construction Feasibility and Costs by Rock Type	PBQD
TM-36/19	Thermal Analyses	SAI
TM-36/20	Thermo-mechanical Stress Analysis and Development of Thermal Loading Guidelines	D&M
TM-36/21	Ground Water Movement and Nuclide Transport	D&M
TM-36/22	Nuclear Considerations for Repository Design	SAI
TM-36/23	Environmental Effluent Analyses	SAI

*These documents were prepared by Dame & Moore (D&M), 20 Haarlem Avenue, White Plains, New York 10603; Parsons Brinckerhoff Quade & Douglas, Inc. (PBQD), 1 Penn Plaza, New York, New York 10001; and Science Applications, Inc. (SAI), 800 Oak Ridge Turnpike, Oak Ridge, Tennessee 37830.

TABLE OF CONTENTS

	<u>Page</u>
LIST OF VOLUMES	v
LIST OF FIGURES	vi
LIST OF TABLES	xii
ABSTRACT	xiii
PREFACE	xiv
 1.0 INTRODUCTION	 1-1
2.0 FACTORS CONSIDERED IN THERMO-MECHANICAL ANALYSES	2-1
2.1 DESCRIPTION OF WASTE FORMS	2-1
2.1.1 Total Recycle (High-Level Waste-HLW)	2-1
2.1.1.1 Canister Dimensions and Thermal Output	2-1
2.1.1.2 Retrievalability Period	2-2
2.1.1.3 Temperature Limits	2-2
2.1.2 Spent Unprocessed Fuel (SURF)	2-2
2.1.2.1 Canister Dimensions and Thermal Output	2-2
2.1.2.2 Retrievalability Period	2-3
2.1.2.3 Temperature Limits	2-3
2.1.3 Uranium-Only Recycle (High-Level Waste-HLW)	2-3
2.1.3.1 Canister Dimensions and Thermal Output	2-3
2.1.3.2 Retrievalable Period	2-4
2.1.3.3 Temperature Limits	2-4
2.2 SITE CONDITIONS	2-4
2.2.1 Stratigraphy	2-4
2.2.2 In-Situ Stress Field	2-4
2.3 ROCK MASS PROPERTIES	2-4
2.3.1 Size Effect	2-5
2.3.2 Effect of Joints	2-5
2.3.3 Effect of Temperature, Fluid and Confining Pressures	2-6
2.3.4 Time Dependent Phenomena	2-6
REFERENCES	2-7
 3.0 THERMO AND THERMO-MECHANICAL LIMITS	 3-1
3.1 VERY NEAR FIELD LIMITS	3-1
3.1.1 Waste and Canister Thermal Limits	3-1
3.1.2 Retrievalability of Canisters	3-2
3.2 NEAR FIELD LIMITS	3-2
3.2.1 Room Stability	3-2
3.2.2 Pillar Stability	3-3
3.2.3 Closure Rates	3-4
3.2.4 Excavation Behavior Following Retrievalability Period	3-4

TABLE OF CONTENTS (CONT'D.)

	<u>Page</u>
3.3 FAR FIELD LIMITS	3-4
3.3.1 Surface Uplift/Subsidence	3-4
3.3.2 Ground Temperature Rise	3-5
3.3.3 Aquifer Temperature Rise	3-5
3.3.4 Ground Water Flow and Radionuclide Transport	3-5
REFERENCES	3-7
4.0 DESCRIPTION OF ANALYTICAL METHODS	4-1
4.1 LIMITATIONS AND ASSUMPTIONS	4-1
4.2 NUMERICAL METHODS	4-2
4.2.1 Finite Element Method	4-3
4.2.2 Boundary Element Method	4-4
4.2.3 Semi-Analytical Method	4-4
4.3 VERY NEAR FIELD ANALYSES	4-5
4.3.1 Simplifications to Geometry	4-5
4.3.2 Thermo-mechanical Stress Analysis	4-6
4.4 NEAR FIELD ANALYSES	4-6
4.4.1 Constraints on Geometry	4-7
4.4.2 Geometrical Simplifications for Analyses	4-7
4.4.3 Canister Placement Sequence	4-7
4.4.4 Thermo-mechanical Stress Analysis	4-7
4.5 FAR FIELD ANALYSES	4-8
4.5.1 Constraints on Geometry	4-8
4.5.2 Geometrical Simplifications for Analyses	4-8
4.5.3 Canister Placement Sequence	4-8
4.5.4 Thermo-mechanical Stress Analyses	4-9
REFERENCES	4-10
5.0 GRANITE - DETAILS OF ANALYSES	5-1
5.1 SITE CONDITIONS	5-1
5.2 MATERIAL PROPERTIES	5-1
5.3 PROPOSED REPOSITORY GEOMETRY AND CANISTER PLACEMENT	5-2
5.4 VERY NEAR FIELD ANALYSIS	5-2
5.4.1 Thermal Analysis	5-2
5.4.2 Thermo-mechanical Stress Analysis	5-3
5.5 NEAR FIELD ANALYSIS	5-4
5.5.1 Immediate Placement of Canisters	5-4
5.5.1.1 Five Year Retrievable HLW (Total and U-Only Recycle)	5-5
5.5.1.2 Five Year Retrievable SPENT FUEL	5-7
5.5.1.3 Twenty-Five Year Retrievable SPENT FUEL	5-8
5.5.2 Sequential Placement of Canisters	5-9
5.5.2.1 Five Year Retrievable HLW (Total and U-Only Recycle)	5-9
5.5.2.2 Five Year Retrievable SPENT FUEL	5-10
5.5.2.3 Twenty-Five Year Retrievable SPENT FUEL	5-10

TABLE OF CONTENTS (CONT'D.)

	<u>Page</u>
5.6 FAR FIELD ANALYSIS	5-10
5.6.1 Thermal Analyses	5-10
5.6.2 Axisymmetric Analysis	5-11
5.6.2.1 Surface Movements	5-11
5.6.2.2 Estimated Changes in Permeability	5-11
5.6.3 Semi-Analytical Studies	5-12
5.6.3.1 Surface Movements	5-12
REFERENCES	5-14
6.0 SHALE - DETAILS OF ANALYSES	6-1
6.1 SITE CONDITIONS	6-1
6.2 MATERIAL PROPERTIES	6-1
6.3 PROPOSED REPOSITORY GEOMETRY AND CANISTER PLACEMENT	6-3
6.4 VERY NEAR FIELD ANALYSES	6-3
6.4.1 Thermal Analysis	6-3
6.4.2 Thermo-Mechanical Stress Analysis	6-3
6.5 NEAR FIELD ANALYSES	6-3
6.5.1 Immediate Placement of Canisters	6-3
6.5.1.1 Five Year Retrievable HLW (Total and U-Only Recycle)	6-4
6.5.1.2 Five Year Retrievable SPENT FUEL	6-6
6.5.1.3 Twenty Five Year Retrievable SPENT FUEL	6-6
6.5.2 Sequential Placement of Canisters	6-7
6.6 FAR FIELD ANALYSIS	6-8
6.6.1 Thermal Analyses	6-8
6.6.2 Axisymmetric Analysis	6-8
6.6.2.1 Surface Movements	6-9
6.6.2.2 Estimated Changes in Permeability	6-9
6.6.3 Semi-Analytical Studies	6-9
6.6.3.1 Surface Movements	6-10
REFERENCES	6-11
7.0 BASALT - DETAILS OF ANALYSES	7-1
7.1 SITE CONDITIONS	7-1
7.2 MATERIAL PROPERTIES	7-1
7.3 PROPOSED REPOSITORY GEOMETRY AND CANISTER PLACEMENT	7-2
7.4 VERY NEAR FIELD ANALYSES	7-2
7.4.1 Thermal Analysis	7-2
7.4.2 Thermo-Mechanical Stress Analysis	7-3
7.5 NEAR FIELD ANALYSES	7-3
7.5.1 Immediate Placement of Canisters	7-3
7.5.1.1 Five Year Retrievable HLW (Total and U-Only Recycle)	7-4
7.5.1.2 Five Year Retrievable SPENT FUEL	7-5
7.5.1.3 Twenty Five Year Retrievable SPENT FUEL	7-6

TABLE OF CONTENTS (CONT'D.)

	<u>Page</u>
7.5.2 Sequential Placement of Canisters	7-7
7.5.2.1 Five Year Retrievable HLW (Total and U-Only Recycle)	7-7
7.5.2.2 Five Year Retrievable SPENT FUEL	7-7
7.5.2.3 Twenty-Five Year Retrievable SPENT FUEL	7-8
7.6 FAR FIELD ANALYSES	7-8
7.6.1 Thermal Analyses	7-8
7.6.2 Axisymmetric Analysis	7-8
7.6.2.1 Surface Movements	7-9
7.6.2.2 Estimated Changes in Permeability	7-9
7.6.3 Semi-Analytical Studies	7-10
7.6.3.1 Surface Movements	7-10
7.6.3.2 Thermal Profiles	7-11
REFERENCES	7-12
8.0 SUMMARY AND CONCLUSIONS	8-1
8.1 GENERAL	8-1
8.2 THERMAL LOADING GUIDELINES	8-1
8.2.1 Very Near Field	8-1
8.2.2 Near Field	8-2
8.2.3 Far Field	8-2
8.3 LIMITATIONS AND ESTIMATED UNCERTAINTIES OF RESULTS	8-3
8.3.1 Variances of Site Geology	8-3
8.3.2 Variances in Rock Properties	8-3
8.3.3 Limitations of Analytical Studies	8-4
8.4 AREAS OF ADDITIONAL WORK	8-4
8.4.1 Laboratory and Field Tests	8-5
8.4.2 Numerical Analysis	8-5
APPENDIX A: CHECK ON ACCURACY OF FINITE-ELEMENT AND BOUNDARY-ELEMENT PROGRAMS	A-1
A.1 CHECK ON ACCURACY OF FINITE-ELEMENT PROGRAM	A-1
A.1.1 Check on Program Accuracy	A-1
A.1.2 Check on Accuracy of Mesh Size and Boundary Conditions	A-2
A.1.3 Check on Accuracy of Element Density	A-3
A.2 BOUNDARY-ELEMENT PROGRAMS	A-3
A.2.1 Boundary-Element Program for Near-Field Analysis	A-3
A.2.1.1 Check on Program Accuracy	A-4
A.2.1.2 Check on Accuracy of a Single Replacing Multiple Line Heat Sources	A-4
A.2.1.3 Check on Accuracy of Thermal Stress Analysis	A-5
A.3 SEMI-ANALYTICAL PROGRAM FOR FAR-FIELD ANALYSIS	A-6
REFERENCES	A-7

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LIST OF FIGURES

<u>Figure</u>	<u>Page</u>
2-1 Size Effect from Intact to Rock Mass	2-8
2-2 Effects of Joints on Rock Mass Behavior	2-8
2-3 Rock Mass Strength with Temperature	2-9
2-4 Strength of Rock Mass with Confining Pressure	2-9
3-1 Radioactive Waste Thermal Limits	3-8
3-2 Retrievability of Canister	3-9
3-3 Flow Chart for Room Stability Analysis	3-10
3-4 Flow Chart for Pillar Stability Analysis	3-11
3-5 Normal Stress on Fracture in Granite Versus Fracture Permeability	3-12
4-1 Flow Chart of the Interaction Between the Three Different Scale Studies in the Thermo-Mechanical Analyses	4-11
4-2 Interaction Between Heat and Mass Transport and Stress Analysis	4-12
4-3 Discretization of Body Into Finite Elements	4-13
4-4 Discretization of Body Into Boundary Elements	4-13
4-5 Geometrical Arrangement for Canister Emplacement of a Single Row of Canisters in a Waste Corridor	4-14
4-6 Very Near Field Axisymmetric Analysis	4-15
4-7 Flow Chart for Thermo-Mechanical Stress Analysis of Very Near Field	4-16
4-8 Canister and Proposed Transporter Dimensions	4-17
4-9 Stable Excavation Dimensions	4-17
4-10 Canister Placement Sequence in Waste Corridors and Near Access Corridors	4-18
4-11 Flow Chart for Thermo-Mechanical Stress Analysis of Near Field	4-19
4-12 General Layout of Underground Radioactive Waste Repository	4-20
4-13 Axisymmetric Geometrical Simplification for Far Field Analysis	4-21
4-14 Proposed Layout and Placement Sequence of Waste Canisters	4-22
4-15 Flow Chart for Thermo-Mechanical Stress Analysis of Far Field	4-23
5-1 Generic Granite Stratigraphic Section and Composition	5-15
5-2 Assumed Strength of Granite Rock Mass with Temperature	5-16
5-3 Cross Section Through HLW Waste Corridors in Granite	5-17
5-4 Cross Section Through Main Access Corridors and HLW Waste Corridors in Granite	5-18

<u>Figure</u>	<u>Page</u>
5-5 Cross Section Through SPENT FUEL Waste Corridors in Granite	5-19
5-6 Cross Section Through Main Access Corridors and SPENT FUEL Waste Corridors in Granite	5-20
5-7 Detail Around Canister for HLW in Granite for Thermal Analysis	5-21
5-8 Very Near Field Axisymmetric Finite Element Mesh	5-22
5-9 Mesh For Plotted Data	5-23
5-10 Temperature Distribution in Granite Due to Thermal Loading of 145 kW/Acre at 1/2 Year for HLW	5-24
5-11 Thermal Stresses in Granite for Thermal Loading of 145 kW/Acre at 1/2 Year for HLW	5-25
5-12 Mesh Plot A) Partial Mesh and B) Mesh of Area for Plotted Results	5-26
5-13 Extended Mesh with Boundary Conditions - Mesh Extends to the Ground Surface	5-27
5-14 Temperature Distribution for 120 kW/Acre at 5 Years for HLW in Granite	5-28
5-15 Stresses in Granite for HLW - 120 kW/Acre at 5 Years	5-29
5-16 Stresses Due to Lithostatic Stress Field of 2000 PSI - Zero Thermal Stresses	5-30
5-17 Stresses Due to 4000 PSI Horz. 2000 PSI Vert. Field Stresses - Zero Thermal Stresses	5-31
5-18 Estimated Maximum Principal Stresses for Critical Elements	5-32
5-19 Estimated Stresses and Strengths in Center of Critical Element and Determination of Maximum Allowable Thermal Loading for HLW - 5 Year Retrievalability	5-33
5-20 Boundary Stresses and Temperatures of Interior Waste Corridors for Immediate Canister Placement - HLW 190 kW/Acre 5 Years from time last Canister was Placed in Granite	5-34
5-21 Boundary Stresses and Temperatures of Exterior Waste Corridor for Immediate Canister Placement - HLW - 190 kW/Acre 5 Years from time last Canister was Placed in Granite	5-35
5-22 Boundary Stresses and Temperatures of Interior Waste Corridors for Immediate Canister Placement - SPENT FUEL 190 kW/Acre 5 Years from time last Canister was Placed in Granite	5-36
5-23 Boundary Stresses and Temperatures of Interior Waste Corridors for Immediate Canister Placement - SPENT FUEL 100 kW/Acre 25 Years from time last Canister was Placed in Granite	5-37
5-24 Boundary Stresses and Temperatures of Interior Waste Corridors for Canister Placement Sequence - HLW 190 kW/Acre 7 Years from time last Canister was Placed in Granite	5-38
5-25 Boundary Stresses and Temperatures of Exterior Waste Corridors for Canister Placement Sequence - HLW 190 kW/Acre 5 Years from time last Canister was Placed in Granite	5-39
5-26 Boundary Stresses of Main Access Corridors for Canister Placement Sequence - HLW 190 kW/Acre 5 Years from time last Canister was Placed in Granite	5-40

Figure

Page

5-27	Boundary Stresses and Temperatures of Waste Corridors Near by Main Access Corridor for Canister Placement Sequence - HLW 190 kW/Acre 5 Years from time last Canister was Placed in Granite	5-41
5-28	Boundary Stresses of Main Access Corridors for Canister Placement Sequence - SPENT FUEL - 100 kW/Acre; 25 Years from time last Canister was Placed in Granite	5-42
5-29	Boundary Stress and Temperatures of Waste Corridor Near by Main Access Corridors for Canister Placement Sequence - SPENT FUEL 100 kW/Acre 25 Years from time last Canister was Placed in Granite	5-43
5-30	Temperatures with Depth at Center-Line of Axisymmetric Repository in Granite for HLW at Various Elapsed Times - 200 kW/Acre	5-44
5-31	Temperatures with Depth at Center-Line of Axisymmetric Repository in Granite for Spent Fuel at Various Elapsed Times - 200 kW/Acre	5-45
5-32	Axisymmetric Finite Element Mesh for Far Field	5-46
5-33	Plan of Proposed Radioactive Repository	5-47
5-34	Surface Displacement for HLW and SPENT FUEL Repositories with Time in Granite - Calculated by Semi-Analytical Method - 190 kW/Acre	5-48
6-1	Generic Stratigraphic Section Argillaceous Formations	6-12
6-2	Cross Anisotropic (Orthotropic) Material	6-13
6-3	Schematic Illustration of Compressive Strength Anisotropy of an Intact Shale	6-14
6-4	Assumed Compressive Strength of Shale Rock Mass - Ignoring Slip on Bedding	6-15
6-5	Assumed Strength of Shale Rock Mass $\beta = 0^\circ$ and 90° with Temperature	6-16
6-6	Cross Section Through HLW and SPENT FUEL Waste Corridors in Shale	6-17
6-7	Cross Section Through Main Access Corridors and HLW and SPENT FUEL Waste Corridors in Shale	6-18
6-8	Canister Placement Sequence in Waste Corridors and Near Main Access Corridors	6-19
6-9	Temperature Distribution in Shale Due to Thermal Loading of 145 kW/Acre at 1/2 Year for HLW	6-20
6-10	Stresses in Shale Due to Thermal Loading of 145 kW/Acre for HLW	6-21
6-11	Mesh Plot a) Partial Mesh and b) Mesh of Area for Plotted Results	6-22
6-12	Extended Mesh with Boundary Conditions - Mesh Extends to the Ground	6-23
6-13	Temperature Contours at 5 Years 125 kW/Acre for HLW in Shale	6-24
6-14	Stresses for Shale Due to Thermal Loading of 125 kW/Acre at 5 Year for HLW	6-25
6-15	Stresses Due to Lithostatic Stress Field of 1500 PSI - Zero Thermal Stresses	6-26

<u>Figure</u>	<u>Page</u>
6-16 Temperature Contours at 25 Years - 90 kW/Acre for SPENT FUEL in Shale	6-27
6-17 Stresses Due to 90 kW/Acre at 25 Years with Lithostatic Stress Field of 1500 PSI - SPENT FUEL in Shale	6-28
6-18 Temperatures with Depth at Center Line of Axisymmetric Repository in Shale for HLW at Various Elapsed Times - 100 kW/Acre	6-29
6-19 Temperatures with Depth at Center Line of Axisymmetric Repository in Shale for SPENT FUEL at Various Elapsed Times - 100 kW/Acre	6-30
6-20 Plan of Proposed Radioactive Repository	6-31
6-21 Surface Displacement for HLW and Spent Fuel Repositories with Time in Shale - Proposed Repository - 120 kW/Acre	6-32
7-1 Generic Stratigraphic Section - Basalt	7-13
7-2 Assumed Strength of Basalt Rock Mass with Temperature	7-14
7-3 Cross Section Through HLW Waste Corridors in Basalt	7-15
7-4 Cross Section Through Main Access Corridors and HLW Waste Corridors in Basalt	7-16
7-5 Cross Section Through SPENT FUEL Waste Corridors in Basalt	7-17
7-6 Cross Section Through Main Access Corridors and SPENT FUEL Waste Corridors in Basalt	7-18
7-7 Extended Mesh with Boundary Conditions - Mesh Extends To Ground Surface	7-19
7-8 Mesh Plot for Sixty Foot Pillar Geometry - Area of Plotted Data for Basalt	7-20
7-9 Temperature Contour Plot for Total Recycle at 5 Years - 190 kW/Acre in Basalt	7-21
7-10 Temperature Contour Plot for U-Only Recycle at 5 Years - 190 kW/Acre in Basalt	7-22
7-11 Stresses for Total Recycle at 5 Years - 190 kW/Acre in Basalt	7-23
7-12 Stresses for U-Only Recycle at 5 Years - 190 kW/Acre in Basalt and Field Stresses	7-24
7-13 Boundary Stresses and Temperatures of Interior Waste Corridors for Immediate Canister Placement - HLW 190 kW/Acre 5 Years from time last Canister was Placed	7-25
7-14 Boundary Stresses and Temperatures of Exterior Waste Corridor for Immediate Canister Placement - HLW - 190 kW/Acre 5 Years from time last Canister was Placed	7-26
7-15 Mesh Plot for Twenty Five Foot Pillar Geometry of Area for Plotted Results	7-27
7-16 Temperature Contour Plot for SPENT FUEL - 5 Years - 190 kW/Acre - in Basalt	7-28
7-17 Stresses for SPENT FUEL - 5 Years - 190 kW/Acre and Field Stresses in Basalt	7-29
7-18 Boundary Stresses and Temperatures of Interior Waste Corridors for Immediate Canister Placement - SPENT FUEL 190 kW/Acre 5 Years from time last Canister was Placed	7-30

<u>Figure</u>	<u>Page</u>
7-19 Temperature Contour Plot for SPENT FUEL - 25 Years - 100 kW/Acre	7-31
7-20 Stresses for Spent Fuel at 25 Years - 100 kW/Acre and Field Stresses in Basalt	7-32
7-21 Boundary Stresses and Temperatures of Interior Waste Corridors for Immediate Canister Placement - SPENT FUEL 100 kW/Acre 25 Years from time last Canister was Placed	7-33
7-22 Boundary Stresses and Temperatures of Interior Waste Corridors for Canister Placement Sequence - HLW 190 kW/Acre 5 Years from time last Canister was Placed	7-34
7-23 Boundary Stresses and Temperatures of Exterior Waste Corridors for Canister Placement Sequence - HLW 190 kW/Acre 7 Years from time last Canister was Placed	7-35
7-24 Boundary Stresses of Main Access Corridors for Canister Placement Sequence - HLW 190 kW/Acre 5 Years from time last Canister was Placed	7-36
7-25 Boundary Stresses and Temperatures of Waste Corridors Near by Main Access Corridor for Canister Placement Sequence - HLW 190 kW/Acre 5 Years from time last Canister was Placed	7-37
7-26 Boundary Stresses of Main Access Corridors for Canister Placement Sequence - SPENT FUEL 100 kW/Acre 25 Years from time last Canister was Placed	7-38
7-27 Boundary Stress and Temperatures of Waste Corridor Near by Main Access Corridors for Canister Emplacement Sequence - SPENT FUEL 100 kW/Acre 25 Years from time last Canister was Placed	7-39
7-28 Temperatures with Depth at Center Line of Axisymmetric Repository in Basalt for HLW at various elapsed times - 190 kW/Acre	7-40
7-29 Temperatures with Depth at Center Line of Axisymmetric Repository in Basalt for SPENT FUEL at various elapsed times - 190 kW/Acre	7-41
7-30 Plan of Square Underground Waste Repository	7-42
7-31 Plan of Proposed Radioactive Repository	7-43
7-32 Maximum Surface Displacement for HLW and SPENT FUEL for Square and Proposed Repositories with Time in Basalt	7-44
7-33 Temperature Profiles at a Depth 1000' for HLW at 500, 1000 and 3000 Years	7-45
7-34 Temperature Profiles at a Depth 1450' for HLW at 500, 1000 and 3000 Years	7-46
7-35 Temperature Profiles at a Depth 1800' for HLW at 500, 1000 and 3000 Years	7-47
7-36 Temperature Profiles at a Depth 2000' for HLW at 500, 1000 and 3000 Years	7-48
7-37 Temperature Profiles at a Depth of 1000' for SPENT FUEL at 1000, 5000 and 10,000 Years	7-49

<u>Figure</u>	<u>Page</u>
7-38 Temperature Profiles at a Depth of 1450' for SPENT FUEL at 1000, 5000, and 10,000 Years	7-50
7-39 Temperature Profiles at a Depth of 1800' for SPENT FUEL at 1000, 5000, and 10,000 Years	7-51
7-40 Temperature Profiles at a Depth of 2000' for SPENT FUEL at 1000, 5000, and 10,000 Years	7-52
A-1 Hollow Cylinder with Linear Temperature Gradient - Plane Strain	A-8
A-2 Comparison of Finite Element and Analytical Solutions Plane Strain	A-9
A-3 Hollow Cylinder with Linear Temperature Gradient - Axisymmetric	A-10
A-4 Mesh Plot a) Partial Mesh and b) Mesh of Area for Plotted Results	A-11
A-5 Boundary Conditions a) Free and b) Fixed at Top Boundary	A-12
A-6 Temperature Distribution 1-120 kW/Acre at 5 Years for HLW	A-13
A-7 Stresses for Temperature Distribution 1. For Boundary Condition A-120 kW/Acre at 5 Years for HLW-Free to Boundary	A-14
A-8 Stresses for Temperature Distribution 1. For Boundary Condition B-120 kW/Acre at 5 Years for HLW-Fixed Top Boundary	A-15
A-9 Extended Mesh with Boundary Conditions - Mesh Extends to the Ground Surface	A-16
A-10 Stresses for Temperature Distribution 1. For Extended Mesh Configuration - 120 kW/Acre at 5 Years for HLW	A-17
A-11 Vertical Stresses in Mid-Height of Pillar for a Unit Vertical Stress Field	A-18
A-12 Circular Tunnel in A Uniaxial Stress Field	A-19
A-13 Single Circular Tunnel with Canister Modelled by a) Single Line Heat Source and b) Multiple Heat Source	A-20
A-14 HLW and SPENT FUEL Power Decay with Time for 5 Years	A-21
A-15 SPENT FUEL Power Decay with Time for 25 Years	A-22
A-16 Comparison of Boundary Stresses and Temperatures for the B.E. and F.D./F.E. Methods - HLW 190 kW/Acres at 5 Years in Granite	A-23

LIST OF TABLES

<u>TABLE</u>	<u>PAGE</u>
5-1 Rock Mass Properties for Generic Granite	5-49
6-1 Rock Mass Properties for Generic Shale	6-33
7-1 Rock Mass Properties for Generic Basalt	7-53
8-1 Acceptable Canister Thermal Loads	8-6
8-2 Acceptable Near Field Thermal Loadings	8-6
8-3 Calculated Maximum Surface Uplifts	8-7
A-1 Comparison of Axisymmetric Finite Element and Analytical Solutions	A-24
A-2 Circumferential Stresses Around a Circular Tunnel in a Uniaxial Stress Field as in Figure A-12	A-25
A-3 Comparison of Circumferential Thermal Stresses and Temperatures Around a Circular Tunnel due to Single and Multiple Line Sources to Represent a Canister as in Figure A-13	A-25
A-4 Strengths and Decay Constants for Modelling HLW	A-26
A-5 Strengths and Decay Constants for SPENT FUEL	A-26
A-6 Computed and Tabulated Power Generations	A-27

ABSTRACT

This volume, TM-36/20 Thermo-mechanical Stress Analysis and Development of Thermal Loading Guidelines, is one of a 23-volume series, "Technical Support for GEIS: Radioactive Waste Isolation in Geologic Formations, Y/OWI/TM-36" which supplements a "Contribution to Draft Generic Environmental Impact Statement on Commercial Waste Management: Radioactive Waste Isolation in Geologic Formations, Y/OWI/TM-44." The series provides a more complete technical basis for the preconceptual designs, resource requirements, and environmental source terms associated with isolating commercial LWR wastes in underground repositories in salt, granite, shale and basalt. Wastes are considered from three fuel cycles: uranium and plutonium recycling, no recycling of spent fuel and uranium-only recycling.

The thermo-mechanical analysis of proposed preconceptual repositories in granite, shale and basalt have been undertaken. The analysis was conducted on three different levels of scale i) Very Near Field (canister scale), ii) Near Field (excavation scale) and iii) Far Field (regional scale) studies. Three numerical methods were used to undertake the thermo-mechanical calculations; namely, the finite element method for thermal stress analysis, the boundary element method for thermal and thermal stress analysis and the semi-analytical method also for thermal and thermal stresses analysis. From the thermo-mechanical studies with simplifying assumptions on rock mass behavior where applicable recommendations for areal thermal loadings to assure retrievability of the canisters and long term safety of the repository are given.

PREFACE

Project Background

One of the major problems related to the production of electricity by light-water nuclear reactors is the management of radioactive wastes generated by the use of nuclear fuel. However, the subject is considered amenable to a rational solution, and the technology involved is considered to be well within the capabilities of our present-day technological base.

An important step toward the realization of an effective waste management program is the preparation of the generic environmental impact statement for commercial waste management. A pivotal issue in waste management is the means of providing long-term, permanent storage of these wastes in a manner to best assure their isolation from the biosphere. Analyses spanning two decades have generated the widely supported concept for providing final isolation of these nuclear wastes in deep geologic formations. Therefore, the Office of Waste Isolation* was assigned the responsibility for preparation of those section of this generic statement dealing with deep geologic waste isolation.

The original concept for deep geologic disposal was first advanced in 1957 when a National Research Council Advisory Committee of the National Academy of Sciences suggested the burial of solid radioactive wastes in salt deposits. To date, the majority of the research, development, and demonstration (RD&D) activities have been in salt. The current United States Department of Energy (DOE) National Waste Terminal Storage (NWTS) program calls for the selection of two sites overlying suitable salt formations by 1979, followed by the construction and start-up in 1985 of one NRC-licensed repository designed for the permanent disposal/isolation of commercial nuclear wastes in a salt formation at one of these two sites. In addition to this activity in salt, vigorous RD&D programs have been initiated to determine the appropriateness of various hard rocks as host media for a repository.

*Operated by Union Carbide Corporation-Nuclear Division for the Department of Energy.

The deep-geologic-isolation portion of the generic statement considers repositories located in salt, granite, shale, or basalt. The repositories are designed to handle wastes from the nuclear fuel cycle without reprocessing, in which the spent fuel is considered a waste (no reprocessing) or from either of two fuel cycles that include reprocessing--the cycle with uranium and plutonium recycle and that with only uranium recycle. To prepare this contribution, the Office of Waste Isolation contracted with Dames & Moore, Parsons, Brinckerhoff, Quade & Douglas, Inc. and Science Applications, Inc. In order to prepare this description, generic sites were defined, preconceptual repository designs completed, and resource requirements and effluents from the repositories identified. The preconceptual repository designs for the salt host formation were based on more than two decades of analysis and in-situ experimentation. The data base upon which the repository design for the non-salt host formations were based is much more sparse since repository-oriented analyses of these formations have been proceeding only for the last couple of years. For each of the host rocks additional analyses were performed during the conduct of these studies. Details of this additional technical work are described within the twenty-three volumes of this report.

For an overview of these preconceptual repository design studies, the study objectives and scope, and the major study assumptions, the reader is referred to Volume 1 of this series, the Executive Summary (Y/OWI/TM-36/1).

Volume Summary (Y/OWI/TM-36/20)

The work described in this report for thermo-mechanical analysis of proposed preconceptual repositories in three generic rock types, granite, shale and basalt. The properties and stratigraphic sections of the generic rock types have been compiled from available literature. This data has then been used as the input data base for the studies mentioned in this report. Since the data is generic site specific, data has been omitted unless it would be relevant to a generic site. The lack of data in the rock types considered is because data is only readily available

from areas that are mineralized. Since these areas are considered to be poor sites for a repository; since, a) mineralized zones will attract excavation and investigation of the area, b) if not at present they will possibly be economic in the future and c) the sites are in general more fractured and often associated with major faulting. Therefore because of the limited data on rock mass properties, assumptions where necessary on rock mass behavior have been incorporated into the analyses. The analyses are not highly sophisticated since at this time the data base is not available to warrant complex analyses. However, there are areas where detailed analyses and investigations are required and these are highlighted in the report. Preliminary guidelines for thermal loading that the repository can safely accomodate are introduced and explained. In some cases the guidelines have a sound and solid formation, e.g. past experiences; however, in other cases more information is required to support certain criteria. The area of major concern is criteria for the long term safety of the repository. Recommendations of areal thermal loadings to assure retrievability of the waste forms and long term safety of the repository have been determined. These recommendations are at this stage preliminary and must be updated in the light of experience and further investigations recommended.

1.0 INTRODUCTION

The preconceptual repository design studies for a facility in three host media, granite, shale and basalt, include a number of analyses ranging from radionuclide releases, handling and transportation of the waste forms, mining and other numerical analyses.

This volume contains a description of the thermo-mechanical analyses of the preconceptual repository and the guidelines developed for the safe thermal loading of the repository. Safe thermal loading indicates one in which the retrievability of the canisters and long term safety of the repository are assured.

The report contains a brief description of the waste forms to be stored and assumptions and limitations of the study. Criteria for the development of thermal loading guidelines are given. The methodologies of the analyses are highlighted as well as any interaction between this study and other related studies. The thermo-mechanical stress analyses are described separately for each of the generic rock types. A summary of the results of the analyses is given and suggestions regarding additional work are provided.

2.0 FACTORS CONSIDERED IN THERMO-MECHANICAL ANALYSES

Many factors had to be considered in the thermo-mechanical studies. The major categories included waste forms, site conditions and rock mass properties. These are discussed in the following sections.

2.1 DESCRIPTION OF WASTE FORMS

Three alternative LWR fuel cycles are being considered in this document as the basis for repository design. Details of the waste forms for each of these cycles are described in Volume Y/OWI/TM-36/2. A brief description of the various cycles is included below.

Total Recycle (Cycle I) assumes recycle of uranium and plutonium for further use as fuel. Because of the limited amounts of plutonium available, only a fraction of all LWR's would utilize mixed oxide ($\text{UO}_2 + \text{PuO}_2$) fuel. Conventional enriched uranium dioxide fuels would continue to be a major fuel source.

SURF, Spent Unreprocessed Fuel, Cycle calls for disposal of spent fuel. Reprocessing would not occur. Intact (Cycle II) spent-fuel assemblies with their inventories of fissile uranium and plutonium would be discarded. Uranium-Only Recycle (Cycle III), would recycle the uranium in spent fuel. The recycled uranium would be re-enriched in U-235 and fabricated into fuel. The plutonium in the spent fuel would be discarded with the other reprocessing wastes.

Total recycle and Uranium-only recycle generate wastes of similar physical forms; however, the actinide compositions are different. The Uranium-only recycle wastes contain significant amounts of Plutonium similar to the SURF waste.

2.1.1 Total Recycle (High-Level Waste-HLW)

2.1.1.1 Canister Dimensions and Thermal Output

The Total Recycle (HLW) waste will be in a glass or calcined form. The packaging of this waste will consist of stainless steel canisters approximately 8 inches in diameter for calcined HLW and 12 inches in

diameter for glass HLW. It will be 10 feet long. The age of the waste upon storing in the repository will be 10 years. When any reference to HLW is made in this report, it refers to 10-year-old waste at the time of storage unless specifically mentioned otherwise. The thermal output of a single canister of this HLW will be up to a maximum of 2.5kW. Upon dilution of the HLW, this thermal output can be reduced.

2.1.1.2 Retrievability Period

The repository is to be capable of being operated in a retrievable mode - that is, all emplaced waste can be removed from the repository at about the same rate and with about the same effort as storage placement. The proposed retrievability period of HLW stored in the repository at an age of 10 years is 5 years. Therefore, safe access to a corridor containing HLW must be possible for 5 years after the last canister has been placed in it. Removal of a canister from its borehole must also be possible 5 years after the canister has been stored.

2.1.1.3 Temperature Limits

The calcined and glass wastes will be subjected to significant increases in cracking and leaching rates at elevated temperatures. Therefore, in order to maintain the integrity of the waste, an upper thermal limit to which the waste is subjected will need to be set. Also austenitic stainless steel, such as 304L, is used in HLW canisters. It undergoes changes in structure during long-term exposure in air at elevated temperatures. The observed effect is an increased susceptibility to stress cracking upon subsequent exposure to aqueous solution. Thus a maximum thermal limit to which the stainless steel is subjected will need to be made in order that the canister behaves as required. Actual limits are discussed in 3.1.1.

2.1.2 Spent Unreprocessed Fuel (SURF)

2.1.2.1 Canister Dimensions and Thermal Output

The SPENT FUEL (SURF) waste will consist of intact spent LWR fuel assemblies packaged into steel canisters. The size of these canisters

will be approximately 14 inches in diameter and 16 feet long. The age of the waste upon storing in the repository will be 10 years old, dating from the time of removal from the reactor. When any reference to SPENT FUEL is made in this report, it refers to waste of this age, unless specifically mentioned otherwise. The thermal output of a single canister of SPENT FUEL will depend on whether it is BWR or PWR; however the expected maximum thermal output will be less than 0.8kW/canister.

2.1.2.2 Retrievability Period

As mentioned in Section 2.1.1.2, the repository is to be capable of being operated in a retrievable mode. The two retrievability periods for SPENT FUEL to be considered are 5 and 25 years. Thus, safe access to the canister and retrievability of the canister must be assured over these periods of 5 and 25 years after storage of the SPENT FUEL in the repository.

2.1.2.3 Temperature Limits

The surfaces of the Zircaloy cladding (spent LWR fuel assemblies) will become very reactive during storage within sealed canisters due to the degradation of the protective oxide film at elevated temperatures with the absence of an oxidant. Therefore, upper temperature limits will be required to be set so that the SPENT FUEL assemblies will not become over-reactive. These limits are discussed in 3.1.1.

2.1.3 Uranium-Only Recycle (High Level Waste-HLW)

2.1.3.1 Canister Dimensions and Thermal Output

The Uranium-only recycle waste characteristics are very similar to Total Recycle HLW. The size of canister will be about 8 inches in diameter for calcined HLW and 12 inches in diameter for glass waste. The canister will be 10 feet long. The maximum thermal output per canister will be 2.5kW and can be reduced by dilution. The age of the waste upon storage in the repository will be 10 years old, dating from the time of reprocessing. In this report any reference made to HLW includes both Total Recycle and Uranium-Only Recycle, 10 years old at storage, unless otherwise specified.

2.1.3.2 Retrievability Period

Uranium-Only Recycle waste is to be capable of being retrieved up to 5 years after storage.

2.1.3.3 Temperature Limits

The same comments on temperature limits for Total Recycle HLW (Section 2.1.1.3) are also applicable for Uranium-Only Recycle HLW.

2.2 SITE CONDITION

2.2.1 Stratigraphy

The construction of the generic stratigraphy for each rock type considered, i.e., granite, shale and basalt is discussed in Volume Y/OWI/TM-36/3. These derived or assumed stratigraphies were used in this present study. The specific stratigraphy for each generic rock type is shown in Sections 5.1, 6.1 and 7.1 respectively for granite, shale and basalt. In some cases modifications were made for modelling purposes, e.g., homogeneity was assumed. However, where such assumptions are made, they are clearly stated.

2.2.2 In-Situ Stress Field

Certain in-situ stresses will exist within the rock mass at each repository site. These stresses will have an important effect on the stability of the rooms and must be considered in each stress analysis. Based on values stated in literature, representative in-situ stresses were assumed for each rock type. These values are discussed in Sections 5.1, 6.1 and 7.1 for granite, shale and basalt respectively.

2.3 ROCK MASS PROPERTIES

The rock mass properties for each generic repository rock type are quoted in Sections 5.2, 6.2 and 7.2 for granite, shale and basalt. The derivation of these properties is discussed in detail in companion Volumes Y/OWI/TM-36/5, 6 and 7. To highlight the most important points regarding rock mass properties for thermo-mechanical analyses, a limited discussion is included below.

2.3.1 Size Effect

A rock mass consists of intact blocks of rock assembled into a matrix. When a rock mass is sampled, e.g., in a diamond drilling program, small intact pieces of core of rock are obtained. The properties of a single intact specimen of rock and the total rock mass (see Figure 2-1) differ substantially because of the size effect. That is, the discontinuities and flaws (a greater number of them in a larger volume) are not taken into account in the smaller specimen. Therefore, unless tests have been conducted on large samples, e.g. in-situ tests, properties of the rock mass are virtually unknown. However, approximations of rock mass properties may be made by applying correction factors to intact test values. There are many cases in rock mechanics on the subject of size effect and some of these references are quoted in the companion volumes on rock properties (see Volumes Y/OWI/TM-36/5, 6 and 7).

The quoted generic rock mass properties assumed for these studies are for a particular volume and size of the rock mass. In these studies the size of a five foot cube specimen of the rock mass was chosen as the basis for all rock mass properties. The five foot cube was chosen because size effects appear to level out for rock volumes this size and larger. Also it may be inappropriate to consider volumes much smaller than this because of the difficulty to define input dimensions, e.g., extent of fractured zone around excavation due to blasting.

2.3.2 Effect of Joints

The effects of major joints or planes of weakness have not been incorporated into this study. However, the effects of minor joints have been included indirectly in the thermo-mechanical analyses by virtue of the size effect. That is, the rock mass properties assumed for these studies have been modified from intact rock properties, taking into account the presence of minor joints and flaws.

The presence of larger joints can be of major significance in rock mass behavior. For example, in Figure 2-2 a pillar is illustrated with a major continuous joint through it. If the shear strength of this joint is exceeded then this pillar will shed load to neighboring pillars.

The analyses in this study do not consider such major joints because distribution, extent etc. of these joints is site specific. In addition, sites containing a large number of major joints adversely orientated for stability of the excavations would not be considered for a repository.

2.3.3 Effect of Temperature, Fluid and Confining Pressures

The direct effects of temperature, fluids, confining pressure and pore pressures on rock mass properties are not considered in all aspects of these studies. A limited amount of data of intact rock properties with temperature is available; however, there is little or no data on certain aspects of rock mass behavior considering temperature, fluids, confining pressure and pore pressures. For this reason the dependence of the elastic parameters and coefficient of thermal expansion are treated as constants irrespective of the temperature, presence of water, and the confining pressures. On the other hand, because there is some information on the strength of rock masses with confining pressure and temperature, generic rock mass strengths have been given as dependent on temperature and confining pressure as shown in the example curves illustrated in Figures 2-3 and 2-4.

2.3.4 Time Dependent Phenomena

Time dependent phenomena, such as creep, has not been incorporated into the thermo-mechanical analyses directly. However, the subsequent instability of the excavations after the retrievability period due to both increased thermal loading on the rock and reduction in strength with time has been taken into account. It is assumed that major collapses will be avoided by backfilling the excavations.

2.0 REFERENCES

1. Brady, B.H.G., "An Analysis of Rock Behavior in an Experimental Stopping Block at the Mount Isa Mine, Queensland, Australia", Int. Jn. Rock Mech. Min. Sci & Geomech. Abstr., Vol. 14, pp. 67-75, 1977.
2. Salamon, M.D.G, "Rock Mechanics of Underground Excavation", Advances in Rock Mechanics, 3rd ISRM Symposium, Denver, Vol. I-B, 1974.

FIG. 2-1 SIZE EFFECT FROM INTACT TO ROCK MASS

FIG. 2-2 EFFECTS OF JOINTS ON ROCK MASS BEHAVIOR

FIG. 2-3 ROCK MASS STRENGTH WITH TEMPERATURE

σ_1 - MAXIMUM PRINCIPAL STRESS

σ_3 - MINIMUM PRINCIPAL STRESS

σ_c - UNIAXIAL COMPRESSIVE STRENGTH

A AND k DIMENSIONLESS PARAMETERS DEFINING ABOVE STRENGTH CURVE

NOTE: COMPRESSION POSITIVE

ZERO TENSILE STRENGTH

FIG. 2-4 STRENGTH OF ROCK MASS WITH CONFINING PRESSURE (1)

3.0 THERMAL AND THERMO-MECHANICAL LIMITS

For convenience, the thermal analyses and thermo-mechanical stress analyses were performed on three different scales: 1) Very Near Field, canister scale; 2) Near Field, excavation scale; and 3) Far Field, region scale. At each level of the study, limiting criteria must be established in order to be assured of the satisfactory performance of a repository in both the short and long term time periods. It must be stressed that the following criteria are preliminary assessments of the major limitations to temperature rise, surface movements, fracturing, etc., and, therefore, will be subject to revision as more data is made available.

3.1 VERY NEAR FIELD LIMITS

The Very Near Field study area consists of the immediate vicinity (within several borehole diameters) of the canister. Of importance in this area are the thermal stability and retrievability of the canisters. Another important factor, the shielding protection of the canisters for radioactivity is discussed in volume Y/OWI/TM-36/22 and will not be mentioned here.

3.1.1 Waste and Canister Thermal Limits

The Total Recycle and Uranium-Only Recycle waste forms will be stored in stainless steel canisters as calcined waste or with vitrified glass, as mentioned in Sections 2.1.1 and 2.1.3. Calcined waste becomes unstable at 700°C¹. The stability of the glass, decreases at elevated temperature and especially above 500°C¹. At these elevated temperatures the waste fractures and thus the surface area/volume ratio increases which leads to greater dissolution of the waste. Therefore, a maximum centerline waste temperature has been initially set at 700°C for calcined waste and 500°C for glass waste.

Stainless steel, of which the HLW canisters have been constructed, undergoes extensive stress corrosion at temperatures greater than 375°C. Thus 375°C has been preliminarily prescribed as an upper limit to the temperature the stainless steel can safely be subjected.¹

Spent unprocessed fuel cladding consists of Zircaloy which becomes highly reactive at elevated temperatures. To prevent the cladding from becoming reactive, a maximum thermal limit has been preliminarily set at 200°C.¹

The thermal limits for HLW and SPENT FUEL are illustrated in Figure 3-1.

3.1.2 Retrievability of Canisters

To assure retrievability of the canisters from the borehole; either no rock fracturing can be allowed (since small rock pieces can jam the canister) or support around the canister must be installed. This logic is illustrated in Figure 3-2. If it appears that the in-situ and thermal stresses will cause fracturing around the borehole then the thermal conditions of the waste and canisters must be recalculated since the thermal conductivity of the rock around the borehole will be less than when intact. In this present study, only qualitative and not quantitative computations to predict the extent and/or degree of fracturing around the canister boreholes have been undertaken.

3.2 NEAR FIELD LIMITS

The Near Field study consists of assessing the stability of the excavations (one or several adjacent rooms and pillars) under thermal and in-situ stress loadings. The main points of concern are the safe access to the canisters for the retrievability period and also that major ground disturbance does not occur due to long term instability of the excavations.

3.2.1 Room Stability

The flow chart for determining the relative stability of a room and its sidewalls is shown in Figure 3-3. An excavation is considered stable if either: 1) the stresses in the rock around the opening are limited so that not even minor instabilities will occur or, 2) engineered support designed to assure satisfactory stability is installed.

For repositories in hard, brittle rock, i.e. granite and basalt, it is felt prudent to design so that even the possibility of minor instabili-

ties are eliminated. If minor failures occurred, they would probably take place instantaneously and give rise to additional larger failures before repairs could be made. Accordingly, the stresses around the excavations in these rock types should be limited to no greater than one-half of the rock mass strength. Conversely stated, there should be a minimum strength/stress ratio of 2. The unit volume of the rock mass used to decide on this ratio was selected to be a 5 foot cube of the rock mass. A 5 foot cube was chosen as a unit volume because the rock mass strength decreases only slightly for rock mass volumes greater than this size. This procedure of limiting strength/stress ratios has been successfully applied to many excavations not subjected to thermal loading (2, 3). Provided that the effect of the temperature on rock mass strength and stress-strain behavior are taken into account, this procedure can be applied to the case of an underground repository in hard, brittle rock.

In shale, a weaker, more ductile rock than granite and basalt, it may not be possible to construct excavations in the host rock with the required degree of safety without engineered support. Accordingly, with proper continuous support, the strength/stress ratio in the rock adjacent to the opening may be less than 2. However, without consideration of the effects of support, the strength/stress ratio must be greater than 1 in the major areas of the rock mass within the 5 foot skin around the excavation. It is considered that localized areas of calculated instability will be stabilized by the support system. The support required for stability should be determined by comparing the state of stress around the excavations (in-situ and thermal loading stresses) to the strength of the rock mass. These conditions can then be compared to supported excavations in similar rock types with similar total stress conditions which have been shown to be stable over time periods equal to or longer than the proposed retrievability periods.

3.2.2 Pillar Stability

The stresses within a pillar under in-situ and thermal loading have been computed from the thermo-mechanical analyses. The pillar stability limit considered in these analyses requires the average stress across the mid-height of the pillar to be less than one half of the uniaxial

compressive strength of the pillar at the computed temperature. This criteria was established from past experience ^(2, 3) in pillar design for zero thermal loading. If the edges of the pillar are subjected to stresses greater than one-half of the rock mass strength, then reinforcement of the excavation sidewalls is required to maintain the integrity of the pillar. A flow chart of the pillar stability analysis is shown in Figure 3-4.

3.2.3 Closure Rates

The rate of excavation closure must be such that retrievability of the canisters is not hindered greatly - that is the transporter can traverse a corridor and retrieve canisters during the entire retrievability period.

3.2.4 Excavation Behavior Following Retrievability Period

The behavior of the excavations after the retrievability period must not give rise to extensive fracturing and/or collapse of the rock mass around the excavations. This is to prevent major increases in permeability around the excavations and to limit surface movement. The excavations are to be backfilled. This backfill will provide support to the overall rock mass once minor rock falls around the excavations have occurred. The backfilling and failure material from the rockfalls will inhibit major instability of the rock mass.

3.3 FAR FIELD LIMITS

The Far Field analyses consisted of evaluating the long term safety of the repository considering factors on a regional scale. The factors considered included ground surface heave/subsidence, temperature rises, ground water flow and radionuclide migration. The zone that was studied included the rock mass between 6000 feet below ground level and the ground surface, extending horizontally to the outer control boundary, 3 miles from the center of the repository.

3.3.1 Surface Uplift/Subsidence

The movement of the ground surface due to thermal loading may need to be limited if it gives rise to large disturbances in the rock mass

overlying the repository. Additionally, extensive surface disruption could cause changes in runoff patterns or distress in surface structures and thus needs to be limited. Because the amount of disruption that can be tolerated will depend on the specific site, it is difficult to set a meaningful limit in these generic studies. However, in studies of the salt repository, it has been indicated that vertical surface movements of 4 feet or less probably will not be detrimental to the integrity of the rock layers overlying the repository.⁴

3.3.2 Ground Surface Temperature Rise

In order to preserve natural flora, a limit to temperature rise of the near surface soils (depending on soil type, site environment, flora) will need to be set. As these limiting factors are site specific, absolute criteria cannot be laid down at this time. However, for general guidelines a limit of 1°F temperature rise at the ground surface is assumed to be a reasonable preliminary limit.

3.3.3 Aquifer Temperature Rise

The rise in temperature at the location of water removed from an aquifer must be limited to enable the water to be used without cooling. The factors effecting the limits are; aquifer location, permeability, and flow since these factors are extremely site specific, only general statement regarding aquifer temperatures can be made at this stage. The rise in aquifer temperatures should be held as low as reasonably achievable (ALARA).

3.3.4 Ground Water Flow and Radionuclide Transport

One of the most important factors to be considered in determining the long term safety of a repository is the possible transport of radionuclides to the biosphere. The most likely medium for radionuclide transport is ground water; accordingly, ground water flow resulting from thermal loading has been analyzed in detail in these present studies as described in volume Y/OWI/TM-36/21. However, some important aspects of ground water flow are directly related to rock behavior. They are examined here to illustrate the close interdependence between thermo-mechanical behavior and ground water flow.

The thermal loading of the rock mass will give rise to rock movement resulting in changes in permeability and porosity. An example of the effects that changes in normal load have on the permeability of a fissure in granite ⁵ is illustrated in Figure 3-5. As shown, reduction in the normal stresses across existing fissures in the rock mass will give rise to increases in permeability. If stress analyses indicate that the thermal loadings will result in reductions of normal stresses in the rock mass overlying the repository, then it may be assumed that permeabilities in this zone will be increased. Increases in porosities may also be expected in these areas. These changes must eventually be taken into consideration in the complete analysis of ground water flows. Accordingly, it may become necessary to limit thermal loads in order to minimize the effects of these changes on ground water flow and radio-nuclide migration.

3.0 REFERENCES

1. Jenks, G. H., "Maximum Acceptable Temperatures of Waste and Containers during Retrievable Geologic Storage," Y/OWI/TM-42, Oak Ridge, TN, August 1977.
2. Obert, L. and Duvall, W.I., "Rock Mechanics and the Design of Structures in Rock", New York, Wiley, 1967.
3. Jaeger, J. C. and Cook, N.G.W., "Fundamentals of Rock Mechanics", Chapman & Hall, London, 1971.
4. Russell, J. R., "Areal Thermal Loading Recommendations for Nuclear Wastes Repository in Salt," (in preparation) Y/OWI/TM-37, Oak Ridge, TN, August 1977.
5. Maini, T. and Hocking, G., "An Examination of the Feasibility of Hydrologic Isolation of a High Level Waste Repository in Crystalline Rock", presented at the Geological Disposal of High Level Radioactive Waste Session, Geological Society of America, Seattle, 1977, to be published in Int. Jn. RMMS, 1978 (in press).

Total Recycle

Glass 500°C
Calcine 700°C
Stainless 375°C
Steel Canister

Spent Unreprocessed Fuel

Zircaloy Cladding 200°C

Uranium Only Recycle

Glass 500°C
Calcine 700°C
Stainless 375°C
Steel Canister

FIG. 3-1 RADIOACTIVE WASTE THERMAL LIMITS

FIG. 3-2 RETRIEVABILITY OF CANISTER

FIG. 3-3 FLOW CHART FOR ROOM STABILITY ANALYSIS

FIG. 3-4 FLOW CHART FOR PILLAR STABILITY ANALYSIS

FIG. 3-5 NORMAL STRESS ON FRACTURE IN
GRANITE VERSUS FRACTURE PERMEABILITY (5)

4.0 DESCRIPTIONS OF ANALYTICAL METHODS

As described in 3.0, the thermal and thermo-mechanical analyses were performed for three zones; Very Near Field, Near Field, and Far Field. The relationships of these studies to each other are shown in Figure 4-1. Various numerical methods were used to analyze each zone. These methods, together with their limitations and assumptions are described in this section.

4.1 LIMITATIONS AND ASSUMPTIONS

The complete analysis of rock mass stresses, heat transfer and ground water flow of an underground repository storing radioactive waste can involve complex coupling between the various phenomena. Only a portion of the possible complex of this coupling is illustrated in Figure 4-2. In some instances, decoupling of the phenomena may give rise to large errors. Conversely, uncoupled analyses would be a good representation of the true problem in some cases. For example, a stiff, strong, elastic, nearly impermeable rock mass with little or no non-linear behavior under the expected thermal and stress loads could probably be analyzed satisfactorily with no coupling. Other recent studies of a radioactive waste repository support this idea.¹

In the present study, the three phenomena of heat transfer, mass transfer (ground water flow) and stress analyses were analyzed totally separately. That is, there was no direct coupling of the three phenomena. For example, the heat transfer calculations, (see Volume Y/OWI/TM-36/19), were performed assuming that thermal conduction was the only heat transfer mechanism and that this conduction was unaltered by ground water flow. Also, it was assumed that thermal properties did not change the pressure. In turn, the stress analyses (described in this volume), and the ground water flow analyses (Volume Y/OWI/TM-36/21), used as input the thermal profiles derived from these calculations. In another case, changes in rock mass stresses from the thermal loadings were calculated in the stress analyses. These stress changes and the corres-

ponding changes in permeabilities and porosities were not taken directly into consideration in the ground water calculations.

The effect of uncoupled analyses on the accuracies of the results of these studies cannot be exactly determined at this time. However, it is felt that possible inaccuracies in calculated results will not be great enough to invalidate the general conclusions of these generic studies.

For the present thermo-mechanical stress analyses described in this volume, the following assumptions were considered for all three rock types:

- 1) linear elastic behavior
- 2) either isotropic or orthotropic elastic properties
- 3) no dependance of elastic properties with temperature, pressure or time.
- 4) stressing of the rock mass was due solely to gravity, tectonic, excavation, and thermal loads.
- 5) the effect of pore pressures and phase changes were not modelled.
- 6) many three-dimensional problems were simplified to two dimensions.
- 7) the effect of major joints, faults, etc. were not modelled (i.e., all major discontinuities were assumed to be perfectly welded).
- 8) rock mass properties included the effect of minor flaws (such as minor joints, etc.).

The limitations and assumptions of the present study are discussed separately for each rock type because the relative importance of these factors differs from one rock type to the next.

4.2 NUMERICAL METHODS

The finite difference technique has been used to analyze the heat transfer (Volume Y/OWI/TM-36/19). Three other numerical techniques have been used in the thermo-mechanical stress analyses; finite element, boundary element and a semi-analytical method. The reason for choosing

three different techniques for the thermal stress calculations was because they complimented each other in analyzing the problems and served as checking methods.

The finite element method has been used to analyze the case of immediate canister placement in a large number of excavations. The problems of analyzing the sequencing of the waste canisters would only have been undertaken by the finite element method at high cost. The cost increase would be due to large computer costs for the thermal and thermal stress calculations since problem meshes would need to be large. Therefore, the boundary element method was used to undertake both the thermal and thermal stress analyses of these cases.

For the analysis of the entire repository, the finite difference technique was used to compute the thermal profiles and the finite element method was used to calculate the thermal induced stresses and displacements. However, in order to do this study at reasonable cost, a simplifying assumption in geometry was made; the repository was assumed to be axisymmetrical. For the design three dimensional shape of the repository, a semi-analytical technique was used to analyze the thermal induced stresses, displacements and temperature changes.

4.2.1 Finite Element Method

A very brief description of the Finite Element Method and the program used is included here for completeness. The Finite Element Method consists of subdividing the body to be analyzed into volume elements as shown in Figure 4-3. The stiffness of each of these volume elements is computed and from the conditions of compatibility and equilibrium, the system of equations for the entire problem is constructed. This system of equations is reduced and the stresses and displacements computed at the required locations. The finite element program used throughout this study was SAP4². This program has been checked for problems of thermal stress analysis for both plane and axisymmetric geometries (see Appendix A). The thermal profiles as computed by the finite difference method (see Volume Y/OWI/TM-36/19) have been linearly interpolated to provide the correct thermal input to SAP4. SAP4, which is a linear elastic static or dynamic capable code, then determined the

thermal stress within the rock mass. Quadrilateral elements consisting of four-noded isoparametric elements were used throughout this study. The mesh density around the excavations has been checked against other numerical solutions and found to be in good agreement (see Appendix A).

4.2.2 Boundary Element Method

The boundary element method analyses situations by mapping the problem onto its boundaries by relevant unit solutions. For the problem shown in Figure 4-3, the boundary element program requires discretization of the boundaries by straight line elements as shown in Figure 4-4. The system of equations is constructed for these boundary elements and solved by either iteration or inversion. In the studies described in this report, iteration was the method of reduction of the equations. By using this method, stresses and displacements anywhere in the medium or on the boundary can be computed. The boundary element program used here was originally developed by Bray ³, modified to compute displacements ⁴. It incorporates the solution of a line heat source by Hart ⁵ and has been adapted to solve problems of transient thermo elasticity ⁶. Initially, the problems of the in-situ stress field at infinity and excavation of an opening are analyzed. Secondly, the stresses and temperatures at any point in the medium and on the boundary of the excavation are computed. Finally, the distribution of singularities is altered to remove any normal and surface tractions on the boundary due to the presence of heat sources. The most significant assumption in the present program is that the air in the corridors is assumed to have the same thermal properties as the host rock. As shown in Appendix A the errors involved in this assumption are shown to be small by comparison to results computed previously by finite difference for thermal and finite elements for thermal stress analysis. The accuracy of the boundary element method for the case of a circular tunnel is also illustrated in Appendix A.

4.2.3 Semi-Analytical Method

The program used was the semi-analytical one of St. John ⁷ which models the repository as a number of transient point heat sources. By

superimposing the solutions of: 1) a source at the repository depth and, 2) a sink at twice the depth away from the source in an infinite medium, a solution to a point source beneath a free surface is obtained provided shear tractions are removed on the plane midway between the source and the sink. Therefore, from the closed form solution of temperature, stresses and displacements in an infinite, homogeneous medium, the problem can then be solved. The program finds the relevant shear tractions on the free surface and removes them. Thus the temperatures, stresses and displacements due to any three dimensional shape of the repository can be found.

4.3 VERY NEAR FIELD ANALYSES

The very near field analyses were performed to assess the thermal stability and retrievability of the canisters. From these analyses, the allowable canister thermal output, (heat load), the canister spacing, and the need for support around the canister to assure retrievability were evaluated. The analyses of the very near field geometry consisted of an iterative process between the thermal analyses and the thermal stress analyses. The process started with a thermal analysis of the intact rock assuming an estimated canister heat load (see Volume Y/OWI/TM-36/19). Then a check was made of the canister temperatures. If the temperatures were within the allowable limits, then the thermal stress analysis was conducted. If the canister temperatures were too high, then the canister heat load was reduced or the waste package concept was changed until allowable temperatures were achieved. The thermal stress analysis was conducted to assess the stress conditions within the rock surrounding the canister. If there was no indication of overstressing, or fracturing, then the design was acceptable. If it appeared that fracturing would be too extensive, then the spacing was increased or the canister thermal output was reduced. If it appeared that fracturing of the rock could not be avoided, then support around the canister would be required to assure retrievability.

4.3.1 Simplifications to Geometry

The typical geometry of the placement of high level waste canisters in boreholes in the floor of long parallel corridors is shown in Figure

4-5. From past experience, it appeared that a three-dimensional analysis of this configuration would be required. Since a three-dimensional analysis was beyond the scope of this study, simplifications to the geometry were made in order to analyze the problem two-dimensionally. The geometry shown in Figure 4-6 was analyzed for this study.

4.3.2 Thermo-mechanical Stress Analysis

The flow chart for the thermo-mechanical stress analysis of the very near field is illustrated in Figure 4-7. An axisymmetrical finite element analysis was used to compute the thermal stresses around the borehole shown in Figure 4-6. Then, based on previous numerical analyses of stress distributions around the end of boreholes⁸ the results of the Near Field analyses (Section 4.4) were combined to estimate the stresses for the real case.

4.4 NEAR FIELD ANALYSES

The near field analyses were performed to assess the stability of the excavated rooms and pillars. The stability of the rooms and pillars have a major effect on the safety of the men and equipment during the development, placement, retrieval and backfilling phases of the facilities operations. The analyses of the near field geometry initiated with of a finite difference solution technique to compute heat transfer (see Volume Y/OWI/TM-36/19). The results of these studies were then input into the thermo-mechanical stress analysis. The stresses within the rock mass were limited to avoid room instability according to the guidelines described previously (Section 3.2). Where deemed necessary, engineered support was recommended in order to guarantee safety of the excavations and pillars for the retrievability period. Main access corridors which do not contain HLW or SPENT FUEL canisters were designed to remain stable throughout the entire retrievability period.

4.4.1 Constraints on Geometry

Some of the constraints on excavation and pillar dimensions are illustrated in Figures 4-8 and 4-9. These constraints include:

- 1) Canister dimensions
- 2) Transporter dimensions

- 3) Stable span dimension of the excavations
- 4) Stable height dimensions of the excavations
- 5) Stable pillar dimensions, height and width.

As mentioned in section 2.1 the waste canisters had length dimensions of up to 16 feet. Allowing for clearance when the canister is being transported requires a room height greater than 16 feet. The proposed transporter required a minimum room height of 23 feet and a minimum room width of 18 feet. The stable dimensions of the excavations and pillars depend on rock type, depth, in-situ stress field, thermal loading, etc. and are discussed in Sections 5, 6 and 7.

4.4.2 Geometrical Simplifications for Analyses

In the Near Field (i.e. excavation scale) analysis, two dimensional analyses were undertaken assuming the canisters were equivalent to line heat sources and the borehole was not modelled. Accordingly, the waste corridors were assumed to be infinitely long. Also intersections of waste corridors and access corridors were not analyzed.

4.4.3 Canister Placement Sequence

The placement sequence along the waste corridors is illustrated in Figure 4-10, together with the placement sequence approaching the main access corridors. Even though the waste corridors are filled in a short time (on the order of two weeks for HLW) the possibility of a delay in placement should be considered.

4.4.4 Thermo-mechanical Stress Analysis

The thermo-mechanical stress analysis was undertaken in two parts, 1) for immediate canister placement and 2) for sequential canister placement as shown in Figure 4-11. For the immediate placement of canisters two dimensional thermal analyses were conducted using the finite difference technique (Y/OWI/TM-36/19). The computed thermal profiles from these analyses were then used as input to the finite element stress calculations. For the sequential placement of canisters, the boundary element method was used to analyze both the thermal and thermal stress phenomena.

The reason for undertaking analyses of the canister placement sequence and resulting stress distributions was two fold; firstly to ensure that the excavations will not be overstressed in the retrievability period and secondly, to highlight placement sequences which are detrimental to the behavior of the excavations. For instance, beginning canister placement near the main access corridors and then moving the placement away from these corridors results in higher thermal loads on the access corridors than for the reverse sequencing.

4.5 FAR FIELD ANALYSES

The far field analyses were conducted to compute the movement of the ground surface with time to delineate areas of increased permeability, to evaluate the possibility of rupturing an aquifer above the repository, and to compute the elevation of temperature near the ground surface and within stagnant aquifers. The analyses were undertaken for large time frames (on the order of 10^5 years) to predict the behavior of the rock mass under the thermal loads of HLW and SPENT FUEL.

4.5.1 Constraints on Geometry

A limiting plan area of approximately 2000 acres was set as an upper bound of the extent of the underground repository. Figure 4-12 illustrates the general layout of the proposed underground waste repositories.

4.5.2 Geometrical Simplifications for Analyses

Two different calculations were used to compute the movement of the ground surface. The geometries were different for each type of analysis. For the axisymmetric analyses, the repository was approximated as a large horizontal disc of the same plan area as the proposed repository as shown in Figure 4-13. In the semi-analytical calculations, the true three dimensional design shapes were approximated.

4.5.3 Canister Placement Sequence

The overall canister placement sequence for the entire repository is illustrated in Figure 4-14. The placement sequence begins well

removed from main access corridors and service areas (shafts, maintenance and safety areas etc.) and proceeds towards the center of the repository. The sequence of canister placement was modelled and displacements, stresses, and temperatures in the rock mass above the repository were computed. Also, immediate (insant) placements of canisters was modeled.

4.5.4 Thermo-mechanical Stress Analyses

The thermo-mechanical analyses were conducted with two methods; axisymmetric and three-dimensional. The flow chart of the relationship of these analyses is shown in Figure 4-15. The thermal analyses were conducted by the finite difference technique (see Volume Y/OWI/TM-36/19) and inputted into the axisymmetric finite element analysis; while, the semi-analytical method involved both thermal and thermal stress analyses.

REF: 4-15 (2007)

4.0 REFERENCES

1. Lindblom, U., et al, Ground Water Movements Around A Repository, Final Report, KBS Technical Report 54:06, Hagconsult AB, Stockholm, Sweden, October, 1977.
2. Bathe, K.J., Wilson, E.L., and Peterson, F.E., "SAP4 A Structural Analysis Program for Static and Dynamic Response of Linear System", Report No. EERC73-11 Rev. April 1974, University of California, Berkeley.
3. Bray, J.W., "A Program for Two-Dimensional Stress Analysis using the Boundary Element Method", Rock Mechanics Progress Report No. 16, Rock Mechanics Project, Imperial College, London, 1976.
4. Hocking, G., "BEM8A - J.W. Bray's Boundary Element Program Updated to Calculate Displacements", Rock Mechanics Progress Report No. 17, Rock Mechanics Project, Imperial College, London, 1976.
5. Hart, G., Ph.D. Thesis in Preparation, University of Minnesota, Minnesota, 1977.
6. Hocking, G., "Boundary Element Program for Analysis of Approximate Transient Thermo-Elasticity", Dames & Moore Technical Note No. 12, 1978.
7. St. John, C.M., "Thermo-elastic Analysis of Spent Fuel and High Level Radioactive Waste Repositories in Salt - a Semi-Analytical Solution", Report submitted to Office of Waste Isolation, Union Carbide Corporation - Nuclear Division, Y/OWI/7118/1, 1977.
8. Hocking, G., "Three Dimensional Elastic Stress Distribution around the Flat End of a Cylindrical Cavity", Int. Jn. Rock Mech. Sic. & Geomech. Abstr., Vol. 13, pp. 331-337, 1976.

FIG. 4-1 FLOW CHART OF THE INTERACTION BETWEEN THE THREE
DIFFERENT SCALE STUDIES IN THE THERMO-MECHANICAL ANALYSES

FIG. 4-2 INTERACTION BETWEEN HEAT AND MASS TRANSFER AND STRESS ANALYSIS

FIG. 4-3 DISCRETIZATION OF BODY INTO FINITE ELEMENTS

FIG. 4-4 DISCRETIZATION OF BODY INTO BOUNDARY ELEMENTS

FIG. 4-5 GEOMETRICAL ARRANGEMENT FOR CANISTER EMPLACEMENT
OF A SINGLE ROW OF CANISTERS IN A WASTE CORRIDOR

FIG. 4-6 VERY NEAR FIELD AXISYMMETRIC ANALYSIS

FIG. 4-7 FLOW CHART FOR THERMO-MECHANICAL STRESS ANALYSIS
OF VERY NEAR FIELD

FIG. 4-8 CANISTER AND PROPOSED TRANSPORTER DIMENSIONS

FIG. 4-9 STABLE EXCAVATION DIMENSIONS

FIG. 4-10 CANISTER PLACEMENT SEQUENCE IN WASTE CORRIDORS
AND NEAR MAIN ACCESS CORRIDORS

FIG. 4-11 FLOW CHART FOR THERMO-MECHANICAL STRESS
ANALYSIS OF NEAR FIELD

FIG. 4-12 GENERAL LAYOUT OF UNDERGROUND RADIOACTIVE WASTE REPOSITORY

FIG. 4-13 AXISYMMETRIC GEOMETRICAL SIMPLIFICATION
FOR FAR FIELD ANALYSIS

- NOTES
- ALL CORRIDORS ARE TO BE 10' WIDE
OF EITHER ROOMS OR CORRIDORS
- 2 FOR SHAFT AREA DETAIL, SEE DWG
NO. 610
- 3 BBR = PRESSURIZED WATER REACTOR
WASTE
BBW = BOILING WATER REACTOR WASTE
LLW = LOW LEVEL WASTE
- 4 FOR ROOM CROSS SECTIONS, SEE DWG
NO.
- 5 ROOM SIZES
PRD	56'0" x 78'0" x 10' x 25'
BBR	56'0" x 78'0" x 10' x 25'
LLW	28'0" x 18' x 25'
- ALL CORRIDORS ARE 30' WIDE

FIG. 4-14 PROPOSED LAYOUT AND PLACEMENT SEQUENCE OF WASTE CANISTERS

OFFICE OF WASTE ISOLATION
UNION CARBIDE CORPORATION
NUCLEAR DIVISION
OAK RIDGE, TENNESSEE

PARSONS, BRINCKERHOFF, QUADE & DOUGLAS, INC
NEW YORK, NY

WASTE ISOLATION FACILITY
BRIEF MASTER PLAN

GRANITE-CYCLE II - 3 YR RETRIEVABLE

SCALE: 1" = 500'	CONTRACT NO	
DATE	CDS NO G 9	REV

FIG. 4-15 FLOW CHART FOR THERMO-MECHANICAL STRESS
ANALYSIS OF FAR FIELD

5.0 GRANITE - DETAILS OF ANALYSES

5.1 SITE CONDITIONS

The generic site conditions and stratigraphy for a repository in granite are formulated and described in volume Y/OWI/TM-36/3. The generic granite stratigraphy is illustrated in Figure 5-1. The generic granite rock mass is weathered only to a shallow depth below the surface. The proposed repository is to be located at a depth of approximately 1900 ft. depth.

The in-situ stress conditions at the generic site have been assigned considering general experience in the rock mechanics field ^{1, 2, 3, 4}. The in-situ stresses in granitic rocks are dependent upon depth and previous stress history, particularly tectonic activity. The vertical stress is usually equal to or slightly greater than the overburden pressure. For the generic conditions it has been assumed that the vertical stresses will be equal to the overburden (i.e., depth x unit weight). The horizontal stress is usually expressed as a multiple of the vertical stress; this multiple lies in the range of 0.5 to 2.0 and is generally considerably greater than 1.0 for granite. However, the higher values are usually associated with areas of tectonic activity. Repository siting guidelines preclude locating the repository in areas of tectonic activity. Accordingly, a moderate value of 1.5 has been assumed for the generic studies.

5.2 MATERIAL PROPERTIES

The generic granite rock mass properties are discussed in detail in volume Y/OWI/TM-36/5 and will only be briefly mentioned here in regard to the thermal-mechanical stress analysis. A summary of the assumed granite rock mass properties is shown in Table 5-1.

As discussed in Section 2.3.3, there is a relationship between the compressive strength of a rock mass and the confining pressure. In general this relationship shows an increasing strength for increasing confining pressure. However, to be conservative, this relationship has been ignored in these analyses. The entire rock mass is considered to have only the unconfined compressive strength (no confining pressure) shown in Table 5-1.

The assumed temperature dependence of the rock mass uniaxial compressive strength is illustrated in Figure 5-2. It must be emphasized that this relationship of strength to temperature has been extrapolated from limited data.⁵ As shown in Table 5-1, the assumed tensile strength of the rock mass is zero.

The elastic properties of the granite rock mass are considered to be isotropic. The assumption that the rock mass is linear elastic has been previously discussed (Section 4.1). Since the generic granite is a strong stiff rock at room temperature and pressure, the assumption of linear elasticity for the working loads and temperatures of the proposed repository should be satisfactory. The coefficient of thermal expansion quoted in Table 5-1 was assumed to be isotropic and constant for the range of temperatures and pressures to be expected.

5.3 PROPOSED REPOSITORY GEOMETRY AND CANISTER PLACEMENT

The proposed repository geometry and layout for the preconceptual design studies in granite are detailed in volume Y/OWI/TM-36/10 and 11. The general layout consists of a service area in the center, access and ventilation shafts, maintenance areas, etc., straddled by waste repository corridors on two sides. The placement of waste begins well removed from the service area and proceeds to the main access corridors and finally to the service area and proceeds to the main access corridors and finally to the service area. This placement sequence imposes the least thermal loading on important access areas compared to other placement sequences.

The proposed geometry of the waste corridors and main access corridors for the storage of HLW are shown in Figures 5-3 and 5-4. The proposed geometry of the waste corridors and main access corridors for the storage of SPENT FUEL (SURF) are shown in Figures 5-5 and 5-6.

5.4 VERY NEAR FIELD ANALYSES

5.4.1 Thermal Analysis

The thermal analyses of the Very Near Field geometry are described in volume Y/OWI/TM-36/19. The geometry of the Very Near Field, that is

the area immediately around the canister, is shown in Figure 5-7 for HLW. A similar configuration with different dimensions is proposed for the SPENT FUEL waste. Initially, the thermal analyses were undertaken assuming the rock mass did not fracture. If it was determined from subsequent stress analyses that fracturing occurred, further analyses were undertaken to check whether or not the thermal limits were being exceeded. If the limits were exceeded, the waste density (power output/canister) was reduced.

5.4.2 Thermo-Mechanical Stress Analysis

The thermo-mechanical stress analysis followed the logic described in Section 4.3. The stresses around the canister imposed by thermal loading were computed by an axisymmetric finite element analysis using results from the thermal analyses as input. The axisymmetric finite element mesh for the Very Near Field geometry is shown in Figure 5-8. Figure 5-9 illustrates the area of plotted data. Thermal contours (Figure 5-10) were inputted to the thermal stress analysis for a thermal loading of 145 kW/acre at an elapsed time of 1/2 year after emplacement. This loading represented HLW canisters with thermal outputs of 2.5 kW at a spacing of 10 feet. The thermal stresses around the borehole for this thermal loading are illustrated in Figure 5-11.

The non-thermal stresses around the borehole have been estimated using the results of Near Field analyses (Section 5.5) together with previous numerical results of stresses around boreholes⁶. The combination of the non-thermal with the thermal stresses results in extremely high stresses in the rock immediately around the borehole at small elapsed times for thermal outputs of 2.5 kW/canister (145 kW/acre). The results indicate that for thermal loadings of these values, spalling of the rock around the borehole will most likely occur during the retrievability period. Other studies⁷ have indicated possible rock fracture at a loading of 1 kW/canister and probable rock fracture at a loading of 4 kW/canister, and this lends support to the conclusion reached here.

Within the scope of this present study, the exact extent and degree of fracturing and spalling around the borehole could not be computed. Therefore, two different fractured conditions were analyzed. These

conditions included a 6 and a 12 inch fractured zone around the borehole having thermal conductivity values much less than the intact material (see volume Y/OWI/TM-36/19). For these conditions additional thermal analyses were conducted. If excessive temperatures in the waste canisters were calculated, the thermal output of the canisters was reduced until an acceptable loading was found for each of the two assumed fracture conditions.

The final estimate of the fractured extent around the borehole for the preconceptual design in granite was based on evidence of fracturing around supported excavations^{5, 8}. From this experience it was concluded that a reasonable assumption for the thickness of the fractured zone around a borehole lined with a competent liner would be 6 inches. Therefore, allowable canister thermal loads were assigned using the calculated results for this case.

5.5 NEAR FIELD ANALYSES

The Near Field analyses were performed for both immediate (instant) and sequential placement of canisters. Details of these studies follow.

5.5.1 Immediate Placement of Canisters

The thermo-mechanical analysis of the immediate placement of canisters was undertaken by two different analytical techniques a) thermal analysis by the finite difference technique with the results being inputted into the two dimensional finite element method and b) both thermal and thermal stress analyses undertaken by the boundary element method.

The thermal analysis of the Near Field geometry is described in volume Y/OWI/TM-36/19. The analyses compute the temperature distributions around the excavations for the immediate placement of the waste canisters. The thermal analyses demonstrated that for elapsed times of greater than 3 years, the canister thermal output can be approximated to that of a strip source - that is, the three dimensional problem becomes two dimensional. This approximation can be used for the temperature distributions around the excavation but not for those close to the canisters.

The meshes used for the finite element analysis of the Near Field area are shown in Figures 5-12 and 5-13. The reason why the mesh was continued to the surface is discussed in Appendix A. The boundary element analysis of the Near Field excavation involved twenty-eight straight line elements to model a single excavation.

5.5.1.1 Five Year Retrievable HLW (Total and U-Only Recycle)

The temperature distributions for Total and U-Only Recycle at elapsed times of 5 years are almost exactly the same (volume Y/OWI/TM-36/19). Separate near field analyses were run for each waste form in basalt (Section 7.5.1.1) and support this conclusion. Therefore, for the thermo-mechanical analysis, for granite, both waste forms were treated as the same, i.e. HLW.

The thermo-mechanical analyses of HLW for 5 year retrievability was complicated by the number of variables involved and the unknown sensitivity of the variables to other related parameters. Therefore, it was decided to initially bracket individual parameters with separate finite element studies and combine the results by hand to estimate the allowable thermal loads. The procedure followed was to:

1. Select reasonable room and pillar sizes based on general rock mechanics experience and project requirements. Rooms 20 ft. high and 20 ft. wide with 55 ft. wide pillars were modeled.
2. Perform finite element analyses of thermal stresses after 5 years of storage for thermal loadings of 120 kW/acre and 400 kW/acre (at initial time of placement). Figure 5-14 depicts the temperature distribution for the 120 kW/acre case. The resulting stresses are shown in Figure 5-15.
3. Perform finite element analyses of non-thermal stresses, i.e., in-situ stresses as modified by the excavation. Three cases were modelled; of 2000 psi vertical and 667 psi horizontal, 2000 psi vertical and 2000 psi horizontal (lithostatic), and 2000 psi vertical and 4000 psi horizontal. Results of the last two cases are shown in Figures 5-16 and 5-17 respectively. These studies were required because the

generic horizontal to vertical stress ratio of 1.5 had not been selected at the time work began.

4. Review the results of steps 2 and 3 to see if any pertinent relationships could be seen. Based on this review it was concluded that - a) for both thermal and non-thermal stresses, the most critically stressed elements adjacent to the opening were the top three blocks in the roof, b) in these critical blocks, the thermal and non-thermal maximum and minimum principal stress orientations were nearly identical, i.e., the maximum principal stresses were parallel to the roof surface and the minimum principal stresses were perpendicular to the surface, c) the temperatures and thermal stresses in the critical elements appeared to be almost exactly linearly related to the thermal loadings.
5. Derive the thermal and non-thermal stress relationships so that total stresses at the center of each element could be estimated. This was performed for the critical blocks as illustrated in Figure 5-18.
6. Compare the estimated stress conditions at the center of the critical element to the estimated average strength at the same point to determine the maximum thermal load which would meet the room stability criteria (Section 3.2.1). Typical calculations for this operation are shown in Figure 5-19.
7. Check other elements at same critical thermal load found in step 6 to make sure no other elements are overstressed.

Based on this procedure, an allowable thermal loading of 190 kW/acre was estimated for HLW for 5 year retrievability.

To check the stress calculations used in the foregoing procedure, the above case of in-situ stress field loading of 2000 psi vertical, 3000 psi horizontal and thermal loading of 190 kW/acre for HLW at an elapsed time of 5 years was analyzed by the boundary element method. The results are shown in Figure 5-20. A stress of 8500 psi was computed at the excavation boundary of the same highest stressed rock unit described above. At a point 2.5 feet into the rock mass from this location on the excavation boundary a stress of 7800 psi was calculated. This

compares favorably to the 7500 psi stress computed at that point using the earlier described method. Even though the excavations were shaped slightly different for each analysis, the calculated stresses in the crown did not differ significantly because of the shadowing effect that neighboring excavations had on the horizontal stress field. However, the stresses around the haunch area are significantly different because of the difference in detailing the boundary curve.

The boundary element method was also used to analyze the case of an excavation at the end of a line of waste corridors - that is, a waste corridor that is not shadowed from the high horizontal stress field by neighboring corridors. As indicated in Figure 5-21, the results show that the computed stresses are slightly higher for this exterior corridor than for the interior corridor.

To check pillar stability criterion (Section 3.2.2), the thermal and non-thermal stresses in the pillar at mid-height that were calculated in the finite element studies described above were combined by hand for a thermal loading condition of 190 kW/acre at 5 years of storage time. This procedure followed the same methods illustrated in Figure 5-18. From these studies it was estimated that the average vertical compressive stress was on the order of 3000 psi. The maximum temperature in the pillar was estimated to be 150°F above ambient or 250°F total. Using Figure 5-2, the uniaxial compressive strength of granite was estimated to be 15,000 psi. Accordingly, the estimated strength to stress ratio was calculated to be 5, much greater than the ratio of 2 required to meet the pillar criterion.

5.5.1.2 Five Year Retrievable SPENT FUEL

The temperature distribution for SPENT FUEL (SURF) and HLW are almost the same around the excavations for the same thermal loading at an elapsed time of 5 years (volume Y/OWI/TM-36/19). Therefore, the calculations described in Section 5.5.1.1 would be applicable here if the same geometry for SURF and HLW were envisaged for granite. However, SURF has a larger number of canisters than HLW for the same thermal loading and an increased extraction ratio was necessary to accommodate the greater number of canisters.

The boundary stresses and temperatures around the waste corridors for SURF are illustrated in Figure 5-22. They were calculated by the boundary element method for an areal thermal loading of 190 kW/acre and an in-situ stress field loading of 2000 psi vertical and 3000 psi horizontal. The stresses and temperatures are approximately the same around the excavation as those for HLW as shown in Figure 5-20. Therefore, this thermal loading of 190 kW/acre for SPENT FUEL at an elapsed time of 5 years under the generic in-situ stress field satisfies the room stability criteria.

Using the boundary element method, the thermal and non-thermal stresses were calculated for the pillar at mid-height. The average vertical pillar stress was computed to be less than 4000 psi. The average uniaxial strength of the pillar (calculated as described in 5.5.1.1) was estimated to be 15,000 psi. Therefore, the pillar stability criteria requiring a strength/stress ratio of two or greater was met.

Because the interior waste corridors for SURF are similar to those for HLW as discussed earlier, it follows that the exterior corridors for both wastes will be under similar loading conditions and will have the same circumferential stresses.

5.5.1.3 Twenty-Five Year Retrievable SPENT FUEL

The stresses and temperatures for the case of twenty-five year retrievable SPENT FUEL were calculated by the boundary element method. The stress distribution and temperatures around the excavations for the geometry of waste corridors are illustrated in Figure 5-23 for a SPENT FUEL thermal loading of 100 kW/acre at 25 years and an in-situ stress field loading of 2000 psi vertical and 3000 psi horizontal. The stress and temperature distribution are very similar to the 5 year retrievable SPENT FUEL at a thermal loading of 190 kW/acre shown in Figure 5-22. Therefore, it appears that a 100 kW/acre loading at a 25 year storage time for this geometry and in-situ stress field condition satisfies the room stability criterion. Also, for the same reason stated above in Section 5.5.1.2, the pillar stability criterion has not been violated for this case.

5.5.2 Sequential Placement of Canisters

The analysis of the sequential placement of canisters is important because a) the effect of a delay in placement should be considered and b) the time to store the waste canisters is a significant time compared to the operating life of the repository. The numerical method used for the thermal and thermal stress analyses that consider the effects of canister placement sequence was the boundary element method.

5.5.2.1 Five Year Retrievable HLW (Total and U-Only Recycle)

The two fuel cycles Total and U-Only Recycle were treated as one (HLW) with regard to thermo-mechanical stress analysis of the Near Field geometry. This was because the thermal output over the time frames considered are almost exactly the same. The stress and temperature distributions for an interior waste corridor considering a 1/2 year delay between filling successive corridors are illustrated in Figure 5-24. These results were computed for a thermal loading of HLW of 190 kW/acre and in-situ stress field loading of 2000 psi vertical and 3000 psi horizontal. The case of the exterior corridor with the same placement sequence is shown in Figure 5-25. The stresses for the two cases of interior and exterior waste corridors for the canister placement sequence shown are always less than those for the immediate canister placement (see Figures 5-20 and 5-21). Therefore, the relative stability of the waste corridor for the canister placement sequence considered is better than the stability assuming immediate placement of canisters.

The effects of canister placement on the stability of the main access corridors and adjacent waste corridors are illustrated in Figures 5-26 and 5-27 for a thermal loading of 190 kW/acre of HLW in the waste corridor area. The stress levels around the main access and the nearby waste corridors are within the maximum limits allowed for acceptable room and pillar stability.

5.5.2.2 Five Year Retrievable SPENT FUEL

The calculated stresses and temperatures for the immediate placement of 5 year retrievable SPENT FUEL were similar to those calculated for the immediate placement of 5 year retrievable HLW waste. Therefore, it was

considered unnecessary to compute the canister placement sequence effect for 5 year retrievable SPENT FUEL. It's assumed that the results would be similar to those illustrated in Section 5.5.3.1 for the waste and main access corridors.

5.5.2.3 Twenty-Five Year Retrievable SPENT FUEL

The boundary stresses around the main access corridors (considering the canister placement sequence) due to thermal loading of 100 kW/acre and the assumed in-situ stress fields are illustrated in Figure 5-28. The temperature rise around the boundary of the main access corridors is less than 15°F above the ambient temperature. The boundary stress and temperatures around the nearby waste corridors are shown in Figure 5-29. In both the waste and main access corridors, the boundary stresses and temperatures do not exceed the room and pillar stability criteria.

5.6 FAR FIELD ANALYSES

Two types of analyses were conducted to study the far field problems. These were: 1) a two-dimensional axisymmetric study of a circular shaped repository, and 2) a three-dimensional approximation using a semi-analytical method which modeled the designed shape of the repository. These studies were preceeded by thermal analyses.

5.6.1 Thermal Analyses

The thermal analysis of the entire repository was undertaken by an axisymmetric finite difference program as described in volume Y/OWI/TM-36/19. The results from this thermal analysis were then input into the axisymmetric finite element program. The temperature distributions calculated by the finite difference program are illustrated in Figures 5-30 and 5-31 for HLW and SPENT FUEL at 200 kW/acre respectively.

The semi-analytical program performed both thermal and thermal stress calculations and was used since it could easily model the correct shape of the proposed repository.

5.6.2 Axisymmetric Analysis

The stresses and displacements in the medium surrounding a circular shaped repository were computed by an axisymmetric finite element program with thermal loading provided as input from the finite difference program. The axisymmetric finite element mesh used for the Far Field calculations is shown in Figure 5-32. Since the form of the analysis required a complete computation of the thermal stress problem for each thermal loading, only a single analysis was computed at the expected time of maximum thermal strain energy. The maximum thermal strain energy was estimated to peak at 1000 yrs. for HLW and 3000 yrs. for SPENT FUEL in granite (see volume Y/OWI/TM-36/19).

5.6.2.1 Surface Movements

The maximum surface displacements for HLW and SPENT FUEL at a thermal loading of 190 kW/acre calculated by the axisymmetric analysis are given below:

Waste Form	Time of Maximum Surface Movement	Maximum Surface Movement
HLW	1000 yrs	1.1 ft
SPENT FUEL	3000 yrs	3.1 ft

5.6.2.2 Estimated Changes in Permeability

Due to changes in normal stresses across pre-existing joints, the permeability of a rock mass can change substantially (see Figure 3-5). Thus changes in rock mass permeability would be caused by stress changes due to the excavation and thermal loading.

Results from the axisymmetric analysis show that tensile stresses exist in the θ direction, (i.e. perpendicular to the rz plane shown in Figure 5-32) from the ground surface to depths in excess of 1000 feet. However, tensile stresses cannot be accommodated by an actual rock mass with joints because the pre-existing joints may open, increasing vertical permeability and load redistribution may occur. Since the axisymmetric analysis did not account for joints and a no-tension analysis was not undertaken, the only conclusion that can be reached from these studies is

that the calculated tensile stress region provides only an approximation of the volume of rock that could be destressed.

It must be emphasized that the horizontal stress field for the generic conditions used in this analysis was assumed to be 1.5 times the vertical equivalent overburden pressure. It is possible that at some sites the horizontal stress at shallow depths may be much greater than 1.5 times the vertical stress. This condition would reduce the changes in rock mass permeability that have been described in this section.

5.6.3 Semi-Analytical Studies

The semi-analytical studies modelled a more accurate shape of the proposed repository design. A plan view of the proposed repository used in the preconceptual design studies is illustrated diagrammatically in Figure 5-33. There is a service zone in the center which contains access shafts and a maintenance area. This service zone is straddled on two sides by areas of radioactive waste storage. Since the problem posed has symmetry with respect to both axes x and y, then only one quarter of the problem was modelled directly.

5.6.3.1 Surface Movements

The calculated surface movements of a point located at approximately $y = 1500$ ft and $x = 0$, (see Figure 5-33), are illustrated in Figure 5-34 for both HLW and SPENT FUEL. These movements were calculated for a thermal loading of 190 kW/ acre. The point selected for study was the position of maximum displacement at any time, based on the analyses performed. The maximum surface displacements are as follows:

Waste Form	Time of Maximum Surface Movement	Maximum Surface Movement
HLW	500 yrs	0.68 ft
SPENT FUEL	2000 yrs	1.90 ft

The large differences between these computed values of surface displacement and those from the finite difference/finite element axisymmetric analyses are apparently due to the differences in geometry. In Section 7.6.4 the cases for both a square shape and the proposed rectangular repository shape shown in Figure 5-33 have been analyzed. The results indicated that the maximum surface displacement computed for the rectangular repository was two thirds of the surface displacement for the square repository. Using this relationship, the values of 0.68 ft and 1.90 ft listed above would become 1.0 ft and 2.8 ft respectively for a square repository with the same plan area as the circular repository modelled in the axisymmetric analysis.

5.0 REFERENCES

1. Voights, Barry, Interpretation of In Situ Stress Measurements; Proceedings of the First Congress, International Society of Rock Mechanics; Theme 4, Vol. III, 1966, pp. 332-348.
2. Hooker, Verne E., David L. Bickel, and James R. Aggson, In Situ Determinations of Stresses in Mountainous Topography; U.S. Dept. of Interior, Bureau of Mines, R.I. 7654, 1970, 19 p.
3. Obert, Leonard and Wilber I. Duvall; Rock Mechanics and Design of Structures in Rock; J. Wiley & Sons Inc., New York; 1967.
4. Lindner, Ernest N., In Situ Stress: A Compilation; International Journal of Rock Mechanics and Mining Sciences, 1978, (in press).
5. Jaeger, J.C., and Cook, N.G.W., "Fundamentals of Rock Mechanics", Chapman & Hall, London, 1971.
6. Hocking, G., "Three Dimensional Elastic Stress Distribution around the Flat End of a Cylindrical Cavity", Int. Jn. Rock Mech. Sci. & Geomech. Abstr., Vol. 13, pp. 331-337, 1976.
7. Cook, N.G.W., "An Appraisal of Hard Rock for Potential Underground Repositories of Radioactive Wastes", Lawrence Berkeley Laboratory LBL 7004, UG70, TID 4500-R66, prepared for U.S. Department of Energy, October, 1977.
8. Salamon, M.D.G., "Rock Mechanics of Underground Excavations", Advances in Rock Mechanics, 3rd ISRM Symposium, Denver, Vol. I-B, 1974.

DEPTH BELOW
SURFACE
(FT)

1000

2000

3000

4000

WEATHERED ZONE
(DEPTH IS VARIABLE)

GENERIC MODE

(%)

QUARTZ	30.2
ALKALI FELDSPAR	32.6
PLAGIOCLASE FELDSPAR	30.2
BIOTITE	4.7
MUSCOVITE	1.0
HORNBLENDE	1.1
MAGNETITE	
ZIRCON	
APATITE	
OTHERS	
TOTAL	99.8%

**GENERIC CHEMICAL COMPOSITION
(AVE OF 546 ANALYSES)**

SiO ₂	70.2
TiO ₂	0.4
Al ₂ O ₃	14.5
Fe ₂ O ₃	1.6
FeO	1.8
MnO	0.1
MgO	0.9
CaO	2.0
Na ₂ O	3.5
K ₂ O	4.1
H ₂ O	0.8
P ₂ O ₅	0.2
TOTAL	100.1%

**FIG. 5-1 GENERIC GRANITE STRATIGRAPHIC SECTION
AND COMPOSITION**

FIG. 5-2 ASSUMED STRENGTH OF GRANITE ROCK MASS
WITH TEMPERATURE

FIG. 5-3 CROSS SECTION THROUGH HLW WASTE CORRIDORS IN GRANITE

FIG. 5-1 CROSS SECTION THROUGH MAIN ACCESS CORRIDORS AND
HLW WASTE CORRIDORS IN GRANITE

FIG. 5-5 CROSS SECTION THROUGH SPENT FUEL WASTE CORRIDORS IN GRANITE

FIG. 5-6 CROSS SECTION THROUGH MAIN ACCESS CORRIDORS AND
SPENT FUEL WASTE CORRIDORS IN GRANITE

FIG. 5-7 DETAIL AROUND CANISTER FOR HLW
IN GRANITE FOR THERMAL ANALYSIS

FIG. 5-8 VERY NEAR FIELD AXISYMMETRIC FINITE ELEMENT MESH

FIG. 5-9 MESH FOR PLOTTED DATA

FIG. 5-10 TEMPERATURE DISTRIBUTION IN GRANITE DUE TO THERMAL
LOADING OF 145KW/ACRE AT 1/2 YEAR FOR HLW

0 1 2CM

STRESS SCALE 1 CM. 5000 PSI.

FIG. 5-11 THERMAL STRESSES IN GRANITE FOR THERMAL LOADING

OF 145KW/ACRE AT 1/2 YEAR FOR HLW

FIG. 5-12 MESH PLOT A) PARTIAL MESH AND
B) MESH OF AREA FOR PLOTTED RESULTS

FIG. 5-13 EXTENDED MESH WITH BOUNDARY CONDITIONS - MESH
EXTENDS TO THE GROUND SURFACE

CONTOURS IN 50° F INCREMENTS
ALL TEMPERATURES ABOVE AMBIENT

FIG. 5-14 TEMPERATURE DISTRIBUTION FOR 120KW/ACRE
AT 5 YEARS FOR HLW IN GRANITE

STRESS SCALE 1CM = 1667 PSI

0 1 2 CM

FIG. 5-16 STRESSES IN GRANITE FOR HLW - 120 KW/ACRE
AT 5 YEARS

FIG. 5-16 STRESSES DUE TO LITHOSTATIC STRESS FIELD OF
2000 PSI - ZERO THERMAL STRESSES

0 1 2 CM

STRESS SCALE 1cm = 3100 psi

FIG 5-17 STRESSES DUE TO 4000 PSI. HORIZ. 2000 PSI VERT.

FIELD STRESSES - ZERO THERMAL STRESSES

- Notes:
- a) Non-thermal stresses estimated at points 1, 2 and 3 by finite element method - assumed vertical stress equal to 2000 psi.
 - b) Final assumed horizontal to vertical stress ratio selected to be 1.5. Therefore, maximum principal stresses estimated to be 4500 psi.
 - c) Thermal stresses estimated at points 4 and 5 by finite element method for 120 and 400 kW/acre - initial thermal loading for HLW at 5 year storage time.
 - d) Thermal and non-thermal maximum principal stresses in critical element are nearly horizontal.

Critical
Element Analyzed

FIG. 5-13 ESTIMATED MAXIMUM PRINCIPAL STRESSES
FOR CRITICAL ELEMENTS

- Notes:
- a) Stresses shown are maximum principal stresses.
 - b) For room stability criteria, strength/stress ratio ≥ 2 . Therefore, total stresses must not exceed 1/2 of estimated rock mass strength.
 - c) 4500 non-thermal stresses for in-situ field stresses of 2000 vertical - 3000 horizontal.
 - d) Points 1 and 2 on stress curve from F.E.M. analyses. Stresses were added to non-thermal stresses.
 - e) Points 3, 4 and 5 on strength curve estimated from Figure 5-2 and assumption of linear relationship between thermal load and temperature of rock mass. Effects of confining pressure (minor principal stresses) on strength ignored.
 - f) Assumed ambient temperature of 100°F.

Critical
Element Analyzed

FIG. 5-19 ESTIMATED STRESSES AND STRENGTHS IN CENTER OF CRITICAL ELEMENT AND DETERMINATION OF MAXIMUM ALLOWABLE THERMAL LOADING FOR HLW - 5 YEAR RETRIEVABILITY

5-34

FIG. 5-20 BOUNDARY STRESSES AND TEMPERATURES OF INTERIOR WASTE CORRIDORS
FOR IMMEDIATE CANISTER PLACEMENT - HLW 190KW/ACRE 5 YEARS
FROM TIME LAST CANISTER WAS PLACED IN GRANITE

INSITU STRESS FIELD
 HOR = 3000 psi
 VER = 2000 psi

SCALES: 0 1 2 cm
 STRESSES 1cm. REP 3000 psi
 TEMP 1cm. REP 90°F

PLOTTED EXCAVATION

TIME CANISTER
 PLACED (YRS) 0 0 0 0 0 0 0 0

BOUNDARY STRESSES

BOUNDARY TEMPERATURES ABOVE AMBIENT

FIG. 5-21 BOUNDARY STRESSES AND TEMPERATURES OF EXTERIOR WASTE CORRIDOR
 FOR IMMEDIATE CANISTER PLACEMENT - HLW - 190 KW/ACRE 5 YEARS FROM
 TIME LAST CANISTER WAS PLACED IN GRANITE

FIG. 5-22 BOUNDARY STRESSES AND TEMPERATURES OF INTERIOR WASTE
 CORRIDORS FOR IMMEDIATE CANISTER PLACEMENT - SPENT FUEL
 190KW/ACRE 5 YEARS FROM TIME LAST CANISTER WAS PLACED IN GRANITE

INSITU STRESS FIELD
 HOR = 3000 psi
 VER = 2000 psi

SCALES: 0 1 2 cm
 STRESSES 1 cm REP 3000 psi
 TEMP 1 cm REP 90°F

CORRIDORS EXTEND OUTWARDS ←
 TIME CANISTER
 PLACED (YRS) 0 0 0 0 0 0 0 0
 PLOTTED EXCAVATION →

FIG. 5-23 BOUNDARY STRESSES AND TEMPERATURES OF INTERIOR WASTE CORRIDORS FOR
 IMMEDIATE CANISTER PLACEMENT - SPENT FUEL 100KW/ACRE
 25 YEARS FROM TIME LAST CANISTER WAS PLACED IN GRANITE

FIG. 5-24 BOUNDARY STRESSES AND TEMPERATURES OF INTERIOR WASTE CORRIDORS
FOR CANISTER PLACEMENT SEQUENCE - HLW 190KW/ACRE 7 YEARS FROM TIME
LAST CANISTER WAS PLACED IN GRANITE

INSITU STRESS FIELD
HOR = 3000 psi
VER = 2000 psi

SCALES 0 1 2 cm
STRESSES 1cm. REP 3000 psi
TEMP 1cm. REP 90°F

PLOTTED EXCAVATION

TIME CANISTER
PLACED (YRS) 0 0.5 1.0 1.5 2.0 2.5 3.0 3.5

BOUNDARY STRESSES

BOUNDARY TEMPERATURES ABOVE AMBIENT

FIG. 5-25 BOUNDARY STRESSES AND TEMPERATURES OF EXTERIOR WASTE

CORRIDORS FOR CANISTER PLACEMENT SEQUENCE - HLW 190KW/ACRE 5 YEARS FROM TIME
LAST CANISTER WAS PLACED IN GRANITE

INSITU STRESS FIELD
 HOR = 3000 psi
 VER = 2000 psi

SCALE: STRESS
 1cm. REP 3000 psi
 0 1 2 cm

FIG. 5-26 BOUNDARY STRESSES OF MAIN ACCESS CORRIDORS FOR CANISTER PLACEMENT SEQUENCE

- HLW 190KW/ACRE 5 YEARS FROM TIME LAST CANISTER WAS PLACED IN GRANITE

FIG. 5-27 BOUNDARY STRESSES AND TEMPERATURES OF WASTE CORRIDORS
NEAR BY MAIN ACCESS CORRIDOR FOR CANISTER PLACEMENT SEQUENCE - HLW
190KW/ACRE 5 YEARS FROM TIME LAST CANISTER WAS PLACED IN GRANITE

FIG. 5-28 BOUNDARY STRESSES OF MAIN ACCESS CORRIDORS FOR CANISTER PLACEMENT SEQUENCE - SPENT FUEL 100KW/ACRE; 25 YEARS FROM TIME LAST CANISTER WAS PLACED IN GRANITE

FIG. 5-29 BOUNDARY STRESS AND TEMPERATURES OF WASTE CORRIDOR NEAR BY MAIN ACCESS CORRIDORS FOR CANISTER PLACEMENT SEQUENCE - SPENT FUEL 100KW/ACRE 25 YEARS FROM TIME LAST CANISTER WAS PLACED IN GRANITE

FIG. 5-30 TEMPERATURES WITH DEPTH AT CENTER-LINE OF
 AXISYMMETRIC REPOSITORY IN GRANITE FOR HLW AT
 VARIOUS ELAPSED TIMES - 200KW/ACRE

FIG. 5-31 TEMPERATURES WITH DEPTH AT CENTER-LINE OF
AXISYMMETRIC REPOSITORY IN GRANITE FOR
SPENT FUEL AT VARIOUS ELAPSED TIMES - 200KW/ACRE

θ DIRECTION PERPENDICULAR TO RZ PLANE

FIG. 5-32 AXISYMMETRIC FINITE ELEMENT MESH FOR FAR FIELD

FIG. 5-33 PLAN OF PROPOSED RADIOACTIVE REPOSITORY

FIG. 5-34 SURFACE DISPLACEMENT FOR HLW AND SPENT FUEL REPOSITORIES WITH TIME
IN GRANITE - CALCULATED BY SEMI-ANALYTICAL METHOD - 190KW/ACRE

TABLE 5-1 ROCK MASS PROPERTIES FOR GENERIC GRANITE

<u>Type of Property</u>	<u>Parameter</u>	<u>Value</u>	<u>Customary English Unit</u>
Index	. Unit Weight	165	lbs/ft ³
	. Natural moisture content	--	%
	. Porosity	0.4	%
Stress-strain	. Young's Modulus	2.5×10^6	lbs/in ²
	. Poisson's Ratio	0.18	---
Strength	. Strength Parameters		
	A	4.5	
	k	0.75	
Thermal	. Unconfined Compressive Strength	19,000	lbs/in ²
	. Tensile Strength	0	lbs/in ²
	. Coefficient of Linear Thermal Expansion	4.5×10^{-6}	°F ⁻¹
	. Heat Capacity		BTU/lb-°F

TEMPERATURE

HEAT CAPACITY

32°F	0.21 BTU/lbs - °F
212	0.22
392	0.23
572	0.25
752	0.26

. Thermal Conductivity

TEMPERATURE

CONDUCTIVITY

32°F	1.65 BTU/hr-ft
122	1.56
212	1.48
302	1.41
392	1.35
572	1.24
752	1.15

Hydrological

. Horizontal permeability	0.06	ft/yr
. Vertical permeability	0.06	ft/yr

6.0 SHALE - DETAILS OF ANALYSES

6.1 SITE CONDITIONS

The generic site conditions for a repository in shale are formulated and described in volumes Y/OWI/TM-36/3. The generic shale stratigraphy is illustrated in Figure 6-1. The generic shale rock mass is overlain by a thin sandstone bed and underlain by a massive limestone sequence. The proposed repository is assumed to be located at approximately 1500 foot depth.

The insitu stress field condition at the generic site was assumed to be lithostatic, i.e., the horizontal stress field equals the vertical stress field. The vertical stress was assumed to be equivalent to the overburden pressure (i.e. depth x unit weight).

6.2 MATERIAL PROPERTIES

The generic shale rock mass properties are discussed in detail in volume Y/OWI/TM-36/6 and will only be briefly mentioned here in regard to the thermo-mechanical stress analysis. Values for the assumed shale rock mass properties are quoted in Table 6-1. The rock mass properties are quoted for an orientation of the shale to the x, y and z axes as indicated in Figure 6-2. The shale rock mass is assumed to be a cross anisotropic (or orthotropic) material which is why five elastic constants have been quoted in Table 6-1.

The strengths of shale apparently depend on the orientation of the maximum principal stress with respect to the bedding.¹ In Figure 6-3, a schematic illustration of the strength anisotropy of an intact shale is shown. The typical modes of failure at the respective angles are included as inserts in this figure. Examples of this phenomenon are discussed in Volume Y/OWI/ TM-36-6.

The assumed generic shale rock mass strength at zero confining pressure is shown in Figure 6-4 for all angles of the maximum principal stress to bedding. The angle β is the angle between the normal to the bedding and the direction of the major principal stress.

The rock mass strength curve shown in Figure 6-4 is assumed to be for a block of rock without preexisting open joints present. However, in a real rock mass, there will be bedding surfaces, some which will have very low cohesive strengths. To account for this in the thermo-mechanical analyses, bedding planes with zero cohesion and a constant friction angle of 20° (see Volume Y/OWI/TM-36-6) were assumed to be present.

As discussed in Section 2.3.3, there is a relationship between the compressive strength of a rock mass and the confining pressure. In general this relationship shows an increasing strength for increasing confining pressure. However, to be conservative, this relationship has been ignored in these analyses. The entire rock mass is considered to have only the unconfined compressive strengths (no confining pressure) shown in Figure 6-4.

The assumed temperature dependence of the rock mass uniaxial compressive strength for an angle of $\beta = 0$ or 90° is shown in Figure 6-5. It must be emphasized that this relationship of uniaxial compressive strength with temperature has been extrapolated from limited data.² Because of this lack of data, the effect of higher temperatures on the mass strength had to be ignored. It is possible that at some critical temperature, depending on the specific mineralogy and water content of the shale, a substantial loss of strength will occur. Unfortunately, no information regarding this phenomenon could be found during the literature review and included in the analyses.

The elastic properties of the shale rock mass are considered to be cross anisotropic. The assumption that the rock mass is linear elastic has been discussed in Section 4.1. Since the generic shale is a moderately strong stiff rock at room temperature and pressure, the assumption of linear elasticity for the working loads and temperatures of the proposed repository should be satisfactory. The coefficient of thermal expansion quoted in Table 6-1 was assumed to be isotropic and constant for the range of temperatures and pressures to be expected.

6.3 PROPOSED REPOSITORY GEOMETRY AND CANISTER PLACEMENT

The proposed repository geometry and layout for the preconceptual design studies are detailed in volumes Y/OWI/TM-36/12 and 13. The proposed geometry of the waste corridors and main access corridors for the storage of HLW and SPENT FUEL are shown in Figure 6-6 and 6-7. The waste placement sequences are illustrated in Figure 6-8.

6.4 VERY NEAR FIELD ANALYSES

6.4.1 Thermal Analysis

The thermal analyses of the Very Near Field geometry are described in volume Y/OWI/TM-36/19 and followed the same methods discussed in Section 5.4.1 in this report.

6.4.2 Thermo-Mechanical Stress Analysis

The thermo-mechanical stress analysis followed the logic set out in Section 4.3. The general procedures used the very near field analyses in granite (Section 4.5.2) were repeated for shale. Computed temperatures distributions and thermal stresses resulting from these analyses are shown in Figures 6-9 and 6-10 respectively. The conclusion from the analyses was that fracturing of the rock would occur for canister thermal outputs of 1.2 to 2.5 kW.

As discussed in Section 5.4.2, additional thermal analyses of the waste forms and canisters were undertaken assuming that a 6 inch annulus of fractured rock existed around the waste canisters.

6.5 NEAR FIELD ANALYSES

6.5.1. Immediate Placement of Canisters

The thermo-mechanical analysis of the immediate placement of canisters was undertaken by only one numerical method in this method, the thermal analysis was conducted by the finite difference technique (volume Y/OWI/TM-36/19) and the results were inputted into the finite element method. The meshes for the finite element analysis of the Near Field case are shown in Figures 6-11 and 6-12. The reason why the mesh was continued to the surface is discussed in Appendix A.

6.5.1.1 Five Year Retrievable HLW (Total and U-Only Recycle)

The temperature distributions for Total and U-Only Recycle at elapsed times of 5 years are almost exactly the same (volume Y/OWI/TM-36/19). Therefore, for the thermo-mechanical analysis, both waste forms were treated as the same, i.e. HLW.

The thermo-mechanical analyses of HLW for 5 year retrievability was complicated by the number of variables involved and the unknown sensitivity of the variables to other related parameters. Therefore, it was decided to initially bracket individual parameters with separate finite element studies and combine the results by hand to estimate the allowable thermal loads. The procedure followed was to:

1. Select reasonable room and pillar sizes based on general rock mechanics experience and project requirements. Rooms 20 ft. high and 20 ft. wide with 60 ft. wide pillars were modeled.
2. Perform finite element analyses of thermal stresses after 5 years of storage for thermal loadings of 90 kW/acre and 125 kW/acre (at initial time of placement). Figure 6-13 depicts the temperature distribution for the 125 kW/acre case. The resulting stresses are shown in Figure 6-14.
3. Perform finite element analyses of non-thermal stresses, i.e., in-situ stresses as modified by the excavation. The assumed generic stress conditions of 1500 psi horizontal stresses and 1500 psi vertical stresses were modeled. Results of this analysis are shown in Figure 6-15.
4. Review the results of steps 2 and 3 to see if any pertinent relationships could be seen. Based on this review it was concluded that - a) for both thermal and non-thermal stresses, the most critically stressed elements adjacent to the opening were the top three blocks in the roof, b) in these critical blocks, the thermal and non-thermal maximum and minimum principal stress orientations were nearly identical, i.e., the maximum principal stresses were parallel to the roof surface and the minimum principal stresses were perpendicular to the surface, c) the temperatures and thermal stresses in the critical elements appeared to be almost exactly linearly related to the thermal loadings.

5. Derive the thermal and non-thermal stress relationships so that total stresses at the center of each element could be estimated for various thermal loads. This was performed for the critical blocks in a manner similar to that used for the analysis for granite (Figure 5-18).
6. Compare the estimated stress conditions at the center of the critical element to the estimated average strength at the same point to determine the maximum thermal load which would meet the room stability criteria for shale (strength/stress = 1.0 or greater). Results indicated that for a loading of 120 kW/acre, thermal stresses of 1700 psi would occur. This value, when combined with non-thermal stresses of 2100 psi would equal the estimated rock strength of 3800 psi in the critical element. The estimated rock strength was derived from Figures 6-4 and 6-5. The critical element was located in the roof of the room, adjacent to the centerline.
7. Check other elements at same critical thermal load found in step 6 to make sure no other elements are overstressed. Because of the very low estimated strength of the shale rock mass where the maximum principal stress is at angles of 30° to 60° to the normal of the bedding, a factor of one for the strength/stress ratio could not be achieved in small zones in the haunch area. However, it was assumed that minor instabilities could be tolerated in the haunch area provided they did not involve large volumes of rock. Minor instabilities do not mean roof failures but that the rock strength in a small volume of rock has been exceeded and load redistribution occurs.

Based on this procedure, an allowable thermal loading of 120 kW/acre was estimated for HLW for 5 year retrievability. However as indicated in Section 3.2.1., engineered support would be required to maintain acceptable room stability. Support needs were based on past experience with excavations in fractured rock subjected to stresses approaching the rock mass strengths.³ The suggested support consists of fully grouted 10-foot rock bolts on a 3-foot grid spacing, together with steel channels and mats. Both the roof and pillar walls should be supported using this system.

To check pillar stability criterion (Section 3.2.2), the thermal and non-thermal stresses in the pillar at mid-height that were calculated in the finite element studies described above were combined by hand for a thermal loading condition of 120 kW/acre at 5 years of storage time. This procedure followed the same methods used in the granite calculations as illustrated in Figure 5-18. From these studies it was estimated that the average vertical compressive stress would be about 1900 psi. The maximum temperature in the pillar was estimated to be 105°F above ambient or 205°F total. Using Figure 6-5, the uniaxial compressive strength of granite was estimated to be 3,800 psi. Accordingly, the estimated strength/stress ratio was calculated to be 2; therefore, pillar criterion was satisfied.

6.5.1.2 Five Year Retrievable SPENT FUEL

The temperature distributions around the excavations at 5 years are almost exactly the same for Total Recycle, U Only Recycle, and SPENT FUEL for the same thermal loading conditions (volume Y/OWI/TM 36-19). Since the temperature distributions are the same then the thermal stresses will be identical. Therefore it is assumed that the safe thermal loading for 5 year retrievable SPENT FUEL in shale is the same as that for HLW i.e. 120 kW/acre. The pillar stability criterion is also satisfied for the same reason.

6.5.1.3 Twenty Five Year Retrievable SPENT FUEL

The initial model studied for SPENT FUEL (SURF) in shale involved a thermal loading of 90 kW/acre at an elapsed time of 25 years after burial. The temperature distribution for this case is shown in Figure 6-16. The combined stresses for the thermal loading and a lithostatic in-situ stress field of 1500 psi are shown in Figure 6-17. These were calculated by the finite element method.

The largest combined maximum principal stress in the roof elements for the case illustrated in Figure 6-17 equals 4350 psi. According to the room stability criterion, this calculated stress is excessive because it is greater than the estimated rock mass strength of 3500 psi (estimated from Figure 6-5 for shale at 110°F above ambient). Therefore it was concluded that the thermal loading must be reduced. The safe thermal loading was estimated by the following procedure:

1. The non thermal major principal stress in the critical element was determined using the results of the finite element studies shown in Figure 6-15. This stress was calculated to be 2100 psi. The remaining stress of 2250 psi (4350 psi minus 2100 psi) equaled the estimated stress due to thermal loading.
2. The allowable thermal stress was calculated by subtracting the non thermal stress from the estimated rock mass strength. Accordingly, 1400 psi was estimated to be the maximum allowable thermal stress.
3. Using the approximate relationship between thermal loading and thermal stress, the allowable thermal load was found by multiplying 90 kW/acre (the initial thermal load) by the ratio of 1400 psi (the allowable thermal stress) to 2250 psi (the initial thermal stress). Accordingly, an allowable thermal load of 55 kW/acre was estimated for SPENT FUEL, 25 years retrievability.

To completely fulfill the room stability criterion for shale, engineered support will be required. This support should be identical to that discussed in Section 6.5.1.1.

The pillar stability criterion was calculated by comparing the average vertical stresses at the pillar mid-height as shown in Figure 6-17 (2000 psi) to the assumed unconfined compressive strength of the rock mass estimated from Figures 6-4 and 6-5 (3500 psi). Although the strength/stress ratio was under 2, it was assumed that the additional rock mass strength gained from confining pressures within the pillar and the stabilizing effects of the engineered support would result in sufficient pillar stability.

6.5.2 Sequential Placement of Canisters

Since the boundary element program used in these studies⁴ is only for the analysis of isotropic media, then the sequential placement of canisters in shale could not be correctly analyzed. However, the sequential placement schemes analyzed for granite and basalt (Section 5.5.3 and 7.5.3 respectively) resulted in less severe loading conditions than those from immediate placement. Therefore it was concluded that sequential placement in shale would also represent more stable situations than those calculated for immediate placement.

6.6 FAR FIELD ANALYSIS

Two types of analyses were conducted to study the far field problems. These were: 1) a two-dimensional axisymmetric study of a circular-shaped repository, and 2) a three-dimensional approximation using a semi-analytical method which modeled the designed shape of the repository. These studies were preceded by thermal analyses.

6.6.1 Thermal Analyses

The thermal analysis of the entire repository was undertaken by an axisymmetric finite difference program as described in volume Y/OWI/TM-36/19. The results from this thermal analysis were then input into the axisymmetric finite element program. The temperature distributions calculated by the finite difference program are illustrated in Figure 6-18 for HLW and Figure 6-19 for SPENT FUEL for thermal loadings at time of burial of 100 kW/acre.

The semi-analytical program performed both thermal and thermal stress calculations and was used since it could easily model the correct shape of the proposed repository.

6.6.2 Axisymmetric Analysis

The stresses and displacements in the medium surrounding a circular shaped repository were computed by an axisymmetric finite element program with thermal distribution provided as input from the finite difference program. The axisymmetric finite element mesh used for the Far Field calculations is shown in Figure 5-32, in the section on granite. Since the form of the analysis required a complete computation of the thermal stress problem for each thermal loading, only a single analysis was computed at the expected time of maximum thermal strain energy. The maximum thermal strain energy was estimated to peak at 1800 yrs. for HLW and 3500 yrs. for SPENT FUEL in granite (see volume Y/OWI/TM-36/19).

6.6.2.1 Surface Movements

The maximum surface displacements for HLW and SPENT FUEL at a thermal loading of 120 kW/acre calculated by the axisymmetric analysis are given below:

Waste Form	Time of Maximum Surface Movement	Maximum Surface Movement
HLW	1800 yrs	1.1 ft
SPENT FUEL	3500 yrs	2.6 ft

6.6.2.2 Estimated Changes in Permeability

Due to changes in normal stresses across pre-existing joints, the permeability of a rock mass can change substantially (see Figure 3-5). Thus changes in rock mass permeability would be caused by stress changes due to the excavation and thermal loading.

Results from the axisymmetric analysis show the existence of tensile stresses in the θ direction, (i.e. perpendicular to the rz plane shown in Figure 5-32) from the ground surface to depths in excess of 200 feet. However, tensile stresses cannot be accommodated by an actual rock mass with joints because the pre-existing joints may open, increasing vertical permeability and load redistribution may occur. Since the axisymmetric analysis did not account for joints and a no-tension analysis was not undertaken, the only conclusion that can be reached from these studies is that the calculated tensile stress region provides only an approximation of the volume of rock that could be destressed.

It must be emphasized that the horizontal stress field for the generic conditions used in this analysis was assumed to be equal to the vertical equivalent overburden pressure. It is possible that at some sites the horizontal stress at shallow depths may be much greater than this assumption. This condition would reduce the changes in rock mass permeability that have been described in this section.

6.6.3 Semi-Analytical Studies

The semi-analytical studies modelled a more accurate shape of the proposed repository design. A plan view of the proposed repository used in the preconceptual design studies is illustrated diagrammatically in

Figure 6-20. There is a service zone in the center which contains access shafts and a maintenance area. This service zone is straddled on two sides by areas of radioactive waste storage. Since the problem posed has symmetry with respect to both axes x and y , then only one quarter of the problem was modelled directly.

6.6.3.1 Surface Movements

The calculated surface movements of a point located at approximately $y = 1500$ ft and $x = 0$, (see Figure 6-20), are illustrated in Figure 6-21 for both HLW and SPENT FUEL. These movements were calculated for a thermal loading of 120 kW/ acre. The point selected for study was the position of maximum displacement at any time, based on the analyses performed. The maximum surface displacements are as follows:

Waste Form	Time of Maximum Surface Movement	Maximum Surface Movement
HLW	700 yrs	0.49 ft
SPENT FUEL	3000 yrs	1.70 ft

The large differences between these computed values of surface displacement and those from the finite difference/finite element axisymmetric analyses are apparently due to the differences in geometry. In Section 7.6.4 the cases for both a square shape and the proposed rectangular repository shape shown in Figure 6-20 have been analyzed. The results indicated that the maximum surface displacement computed for the rectangular repository was two thirds of the surface displacement for the square repository. Using this relationship, the values of 0.49 ft and 1.70 ft listed above would become 0.64 ft and 2.55 ft respectively for a square repository with the same plan area as the circular repository modelled in the axisymmetric analysis.

6.0 REFERENCES

1. Wright, S.C., "A Study of Slope Stability and the Undrained Shear Strength of Clay Shales", PhD Dissertation, University of California, Berkeley, 1969.
2. Jaeger, J.C. and Cook, N.G.W., "Fundamental of Rock Mechanics", Chapman & Hall, London, 1971.
3. Salamon, M.D.G., "Rock Mechanics of Underground Excavations", Advances in Rock Mechanics, 3rd ISRM Symposium, Denver, Vol. I-B, 1974.
4. Hocking, G., "Boundary Element Program for Analysis of Approximate Transient Thermo-Elasticity", Dames & Moore Technical Note No. 12, 1978.

FIG. 6-1 GENERIC STRATIGRAPHIC SECTION ARGILLACEOUS FORMATIONS

FIG. 6-2 CROSS ANISOTROPIC (ORTHOTROPIC) MATERIAL

SCHEMATIC ILLUSTRATION OF
 FIG. 6-3 COMPRESSIVE STRENGTH ANISOTROPY OF AN
 INTACT SHALE

FIG. 6-4 ASSUMED COMPRESSIVE STRENGTH OF SHALE ROCK MASS - IGNORING SLIP ON BEDDING

FIG. 6-5 ASSUMED STRENGTH OF SHALE ROCK MASS.
 $\beta = 0^\circ$ AND 90° WITH TEMPERATURE

FIG. 6-6 | CROSS SECTION THROUGH HLW AND SPENT FUEL WASTE CORRIDORS IN SHALE

FIG. 6-7 CROSS SECTION THROUGH MAIN ACCESS CORRIDORS AND
HLW AND SPENT FUEL WASTE CORRIDORS IN SHALE

FIG. 6-8 CANISTER PLACEMENT SEQUENCE IN WASTE CORRIDORS
AND NEAR MAIN ACCESS CORRIDORS

FIG. 6-9 TEMPERATURE DISTRIBUTION IN SHALE DUE TO THERMAL
LOADING OF 145KW/ACRE AT 1/2 YEAR FOR HLW

0 1 2 CM

STRESS SCALE 1 CM. = 1200 PSI.

FIG. 6-10 STRESSES IN SHALE DUE TO THERMAL LOADING
OF 145KW/ACRE FOR HLW

0 15 30 45 FEET

0 5 10 15 FEET

FIG. 6-11 MESH PLOT: A) PARTIAL MESH AND
B) MESH OF AREA FOR PLOTTED RESULTS

FIG. 6-12 EXTENDED MESH WITH BOUNDARY CONDITIONS -
MESH EXTENDS TO THE GROUND

FIG. 6-13 TEMPERATURE CONTOURS AT 5 YEARS
126KW/ACRE FOR HLW IN SHALE

FIG. 6-14 STRESSES FOR SHALE DUE TO THERMAL LOADING
OF 125KW/ACRE AT 5 YEAR FOR HLW

FIG. 6-15 STRESSES DUE TO LITHOSTATIC STRESS FIELD
OF 1500 PSI - ZERO THERMAL STRESSES

TEMPERATURES °F
EXCLUDING AMBIENT

FIG. 6-16 TEMPERATURE CONTOURS AT 25 YEARS -
90KW/ACRE FOR SPENT FUEL IN SHALE

FIG. 6-17 STRESSES DUE TO 90KW/ACRE AT 25 YEARS WITH LITHOSTATIC STRESS FIELD OF 1500 PSI - SPENT FUEL IN SHALE

FIG. 6-18 TEMPERATURES WITH DEPTH AT CENTER LINE OF
 AXISYMMETRIC REPOSITORY IN SHALE FOR HLW AT
 VARIOUS ELAPSED TIMES - 100KW/ACRE

FIG. 6-19 TEMPERATURES WITH DEPTH AT CENTER LINE OF
 AXISYMMETRIC REPOSITORY IN SHALE FOR SPENT FUEL
 AT VARIOUS ELAPSED TIMES - 100KW/ACRE

FIG. 6-20 PLAN OF PROPOSED RADIOACTIVE REPOSITORY

FIG. 6-21 SURFACE DISPLACEMENT FOR HLW AND SPENT FUEL REPOSITORIES WITH TIME IN SHALE
- PROPOSED REPOSITORY - 120KW/ACRE

TABLE 6-1 ROCK MASS PROPERTIES FOR GENERIC SHALE

Type of Property	Parameter	Value	Customery English Unit	
Index	. Unit Weight	160	lb/ft ³	
	. Natural Moisture Content	2	%	
	. Porosity (effective)	4.0	%	
	. Slake Durability Index (one cycle)	90	%	
		<u>Horizontal*</u>	<u>Vertical*</u>	
Stress-strain	. Young's Modulus	6.0×10^5	3.0×10^5	lb/in ²
	. Poisson's Ratio	0.15	0.15	---
	. Shear Modulus	4.0×10^5		lb/in ²
Strength	. Strength Parameters A	3.0	3.0	---
	. Strength Parameters K	0.75	0.75	---
	. Unconfined compressive strength	4000	4000	lbs/in ²
	. Tensile Strength	0	0	lbs/in ²
Thermal	. Coefficient of linear thermal expansion	4.5×10^{-6}	4.5×10^{-5}	°F ⁻¹
	. Heat capacity	<u>Temperature</u>	<u>Heat Capacity</u>	
		32°F	0.19 BTU/lbs - °F	
		212	0.20	
		392	0.21	
	. Conductivity	<u>Temperature</u>	<u>Conductivity</u>	
			<u>Horizontal*</u>	<u>Vertical*</u>
		32°F	1.12	0.82 (BTU/hr-ft°F)
		122	1.07	0.79
		212	1.02	0.76
		302	1.01	0.75
		392	1.00	0.74
		572	0.99	0.73
		752	0.98	0.72

* See Figure 6-2 for orientation of area with bedding.

7.0 BASALT - DETAILS OF ANALYSES

7.1 SITE CONDITIONS

The generic site conditions for a repository in basalt are formulated and described in volume Y/OWI/TM-36/3. The generic basalt stratigraphy is illustrated in Figure 7-1. The generic basalt rock mass is unweathered in the area of the repository and is overlain by a sandstone aquifer and other basalt flows. The proposed repository is to be located at a depth of approximately 1800 feet.

The in-situ stress field conditions in the generic site were assumed to include a horizontal stress field equal to 1.5 times the vertical stress and a vertical stress equivalent to the overburden pressure (i.e. depth x unit weight).

7.2 MATERIAL PROPERTIES

The generic basalt rock mass properties are discussed in detail in volume Y/OWI/TM-36/7 and will only be briefly mentioned here in regard to the thermal-mechanical stress analysis. A summary of the assumed basalt rock mass properties is shown in Table 7-1.

As discussed in Section 2.3.3, there is a relationship between the compressive strength of a rock mass and the confining pressure. In general this relationship shows an increasing strength for increasing confining pressure. However, to be conservative, this relationship has been ignored in these analyses. The entire rock mass is considered to have only unconfined compressive strength (no confining pressure) corrected for temperature effects.

The assumed temperature dependence of the rock mass uniaxial compressive strength is illustrated in Figure 7-2. It must be emphasized that this relationship of strength to temperature has been extrapolated from limited data.¹ As shown in Table 7-1, the assumed tensile strength of the rock mass is zero.

The elastic properties of the basalt rock mass are considered to be isotropic. The assumption that the rock mass is linear elastic has been previously discussed (Section 4.1). Since the generic basalt is a strong stiff rock at room temperature and pressure, the assumption of linear

elasticity for the working loads and temperatures of the proposed repository should be satisfactory. The coefficient of thermal expansion quoted in Table 7-1 was assumed to be isotropic and consistent for the range of temperatures and pressures to be expected.

7.3 PROPOSED REPOSITORY GEOMETRY AND CANISTER PLACEMENT

The proposed repository geometry and layout for the preconceptual design studies in basalt are detailed in volume Y/OWI/TM-36/14 and 15. The general layout consists of a service area in the center, access and ventilation shafts, maintenance areas, etc., straddled by waste repository corridors on two sides. The placement of waste begins well removed from the service area and proceeds to the main access corridors and finally to the service area and proceeds to the main access corridors and finally to the service area. This placement sequence imposes the least thermal loading on important access areas compared to other placement sequences.

The proposed geometry of the waste corridors and main access corridors for the storage of HLW are shown in Figures 7-3 and 7-4. The proposed geometry of the waste corridors and main access corridors for the storage of SPENT FUEL (SURF) are shown in Figures 7-5 and 7-6.

7.4 VERY NEAR FIELD ANALYSES

7.4.1 Thermal Analysis

The thermal analyses of the Very Near Field geometry are described in volume Y/OWI/TM-36/19. The geometry of the Very Near Field, that is immediately around the canister, is similar to that shown in Figure 5-7 for HLW in granite. A similar configuration except with different dimensions is proposed for the SPENT FUEL waste.

Initially the thermal analyses were undertaken assuming the rock mass did not fracture. If it was determined from subsequent stress analysis that fracturing occurred, further analyses were undertaken to check whether or not the thermal limits for the waste and canister were being exceeded. If the limits were exceeded, the waste density (power output/canister) was reduced to satisfy the thermal criteria.

7.4.2 Thermo-Mechanical Stress Analysis

The thermo-mechanical stress analysis followed the logic and methods set out in Section 2.2.5 and discussed in Section 5.4.2 for granite. From these analyses, it was concluded that high stresses resulting in fracturing would occur in the rock adjacent to the borehole for HLW for thermal outputs of 2.5 kW/canister. The exact extent of the fracturing could not be determined in these studies. However, it was assumed that the fracturing would be limited to a 6 inch annulus in the rock surrounding the canisters providing a steel liner was installed in the borehole.

7.5 NEAR FIELD ANALYSES

The Near Field analyses were performed for both immediate (instant) and sequential placement of canisters. Details of these studies follow.

7.5.1 Immediate Placement of Canisters

The thermo-mechanical analysis of the immediate placement of canisters was undertaken by two different analytical techniques a) thermal analysis by the finite difference technique with the results being inputted into the two dimensional finite element method and b) both thermal and thermal stress analyses undertaken by the boundary element method.

The thermal analysis of the Near Field geometry is described in volume Y/OWI/TM-36/19. The analyses compute the temperature distributions around the excavations for the immediate placement of the waste canisters. The thermal analyses demonstrated that for elapsed times of greater than 3 years, the canister thermal output can be approximated to that of a strip source - that is, the three dimensional problem becomes two dimensional. This approximation can be used for the temperature distributions around the excavation but not for those close to the canisters.

The meshes used for the finite element analysis of the Near Field area are shown in Figures 7-7 and 7-8. The reason why the mesh was continued to the surface is discussed in Appendix A. The boundary element analysis of the Near Field excavation involved twenty-eight straight line elements to model a single excavation.

7.5.1.1 Five Year Retrievable HLW (Total and U-Only Recycle)

The thermal and thermo-mechanical analyses for the 5 year retrievable HLW were undertaken in the following order:

1. Based on a review of the previous analyses of other rock types and the assumed rock mass properties for basalt, an allowable thermal loading was estimated. The review indicated that a thermal loading of 190 kW/acre at time of burial could be used for 5 year retrievable HLW in basalt.
2. Using the 190 kW/acre loading, temperature distributions were calculated by the finite difference method (Y/OWI/TM-36-19) for both total recycle and U-only recycle at a 5 year time lapse. The results are shown on Figures 7-9 and 7-10.
3. With the temperature distributions from Step 2, and the assumed in-situ stress loadings as input, a finite element analysis was performed to calculate the combined thermal and non-thermal principal stresses. The results are shown in Figure 7-11 and 7-12. The similarities in the results substantiated the assumption used in the granite and shale studies that both forms of HLW could be treated as one.
4. To check the room stability criterion (Section 3.2.1), the major principal stresses in the elements adjacent to the opening (Figures 7-11 and 7-12) were compared to the estimated average rock mass strength in the same elements. The rock mass strengths were estimated from Figure 7-2. The lowest strength/stress ratios were found in the 3 elements adjacent to the roof of the opening. In these blocks, the average strength was estimated to be between 17,000 and 18,000 psi at a temperature of 260°F (160°F above the assumed ambient). The major principal stresses in these blocks were calculated to be on the order of 8,500 psi. Therefore the strength/stress ratio was a minimum of 2 and the room stability criterion was satisfied.
5. A cross check of the previously calculated stresses and temperatures was performed using the boundary element method. Both interior and exterior corridors were analysed in this step.

The results are shown on Figures 7-13 and 7-14. For the critical elements previously identified in step 4, the boundary stresses were calculated to be on the order of 9500 psi. The calculations showed that the stresses at a point 2.5 feet into the rock mass in this area are about 8500 psi, the same as calculated in step 4. The stresses in exterior corridors appear to be slightly greater than those around the interior corridors. However, it is believed that the differences are insignificant.

6. The pillar stability criterion (Section 3.2.2) was checked by comparing the estimated uniaxial compressive strength of the rock mass to the average vertical stress at the pillar mid height. The estimated rock mass strength was 17,000 to 18,000 psi (from Figure 7-2 for a temperature of 260°F). The vertical stresses averaged slightly less than 3000 psi (Figure 7-11 and 7-12). Therefore, the strength/stress ratio is about 6, much greater than 2 and the pillar stability criterion is satisfied.

7.5.1.2 Five Year Retrievable SPENT FUEL

The temperature distribution for SPENT FUEL (SURF) and HLW are almost the same around the excavations for the same thermal loading at an elapsed time of 5 years (volume Y/OWI/TM-36/19). Therefore, the calculations described in Section 7.5.1.1 would be applicable here if the same geometry for SURF and HLW were envisaged. However, SURF has a larger number of canisters than HLW for the same thermal loading and an increased extraction ratio was necessary to accommodate the greater number of canisters. Therefore new finite element and boundary element analyses of 190 kW/acre thermal loadings were performed on the revised geometry which incorporated 25 foot-wide pillars. The finite element mesh which was used is shown in Figure 7-15. The boundary element method involved twenty-eight straight line elements. The results of the new analyses are shown in Figures 7-16 through 7-18.

Room and pillar stability criteria were evaluated using the same methods described in Section 7.5.1.1. The results of the room stability evaluation were the same as those for HLW (Section 7.5.1.1). Pillar stability results were slightly different because of the smaller pillar

width (25 ft vs 60 ft). The average vertical stress in the pillars was calculated to be about 4000 psi. The pillar stability criteria is satisfied because the estimated mass strength is 17,000 to 18,000 psi, far greater than twice the vertical stress.

7.5.1.3 Twenty Five Year Retrievable SPENT FUEL

The allowable thermal loading for twenty-five year retrievable SPENT FUEL was determined with the use of both finite element and boundary element analyses. Initially, a thermal loading of 100 kW/acre was estimated from a review of the results of previous studies and the estimates of rock mass properties of basalt.

The temperature distributions around the excavations for the thermal loading of 100 kW/acre of SPENT FUEL at 25 years after burial for the geometry described in Section 7.5.1.2 are shown in Figure 7-19. The thermal contours are for the temperature rise above the geothermal temperature. The stresses calculated by the finite element analyses for the applied thermal load of 100 kW/acre and the assumed in-situ stress field are illustrated in Figure 7-20. The in-situ stress field was assumed to be 2000 psi vertical and 3000 psi horizontal. The maximum critical stress illustrated in Figure 7-20 is 8500 psi in the elements above the roofline. This is slightly less than one half of the estimated rock mass strength (18,000 psi) as given in Figure 7-2; thus, the room stability criterion has not been exceeded.

The pillar stability criterion is satisfied since the average applied vertical stress across the pillar is less than 4000 psi and the estimated uniaxial compressive strength of the pillar (18,000 psi) is far greater than twice this.

The stresses and temperatures for the 100 kW/acre loading were also computed by the boundary element method. The calculated boundary stresses and temperatures for an interior waste corridor are illustrated in Figure 7-21. The maximum boundary stress for this case was 9000 psi for the thermal loading of 100 kW/acre of SPENT FUEL at 25 years and the generic in-situ stress field. At a point 2.5 feet into the rock mass the point where the stresses were calculated in the finite element analyses, stresses were calculated to be 8500 psi.

7.5.2 Sequential Placement of Canisters

The analysis of the sequential placement of canisters is important because a) the effect of a delay in placement should be considered and b) the time to store the waste canisters is a significant time compared to the operating life of the repository. The numerical method used for the thermal and thermal stress analyses that consider the effects of canister placement sequence was the boundary element method.

7.5.2.1 Five Year Retrievable HLW (Total and U-Only Recycle)

The two fuel cycles Total and U-Only Recycle were treated as one (HLW) with regard to thermo-mechanical stress analysis of the Near Field geometry. This was because the thermal outputs over the time frames considered appear almost exactly the same for both cases. The stress and temperature distributions for an interior waste corridor considering a 1/2 year delay between filling successive corridors are illustrated in Figure 7-22. These results were for a thermal loading of HLW of 190 kW/acre and in-situ stress field loading of 2000 psi vertical and 3000 psi horizontal. The case of the exterior corridor with the same placement sequence is shown in Figure 7-23. The stresses for the canister placement sequences shown in Figures 7-22 and 7-23 are always less than those for the immediate canister placement (see Figures 7-11 and 7-12). Therefore, the relative stability of the waste corridor for the canister placement sequence considered here is better than the stability assuming immediate placement of canisters.

The effects of canister placement on the stability of the main access corridors and adjacent waste corridors are illustrated in Figures 7-24 and 7-25 for a thermal loading of 190 kW/acre of HLW. The stress levels around the main access and the nearby waste corridors are within the maximum limits allowed for acceptable room and pillar stability.

7.5.2.2 Five Year Retrievable SPENT FUEL

The calculated stresses and temperatures for the immediate placement of 5 year retrievable SPENT FUEL were similar to those calculated for the immediate placement of 5 year retrievable HLW waste. Therefore, it was considered unnecessary to compute the canister placement sequence effect for 5 year retrievable SPENT FUEL. It is assumed that the results would

be similar to those illustrated in Section 7.5.2.1 for the waste and main access corridors.

7.5.2.3 Twenty-Five Year Retrievable SPENT FUEL

The boundary stresses around the main access corridors (considering the canister placement sequence) due to thermal loading of 100 kW/acre and the assumed in-situ stress fields are illustrated in Figure 7-26 for 25 year retrievable SPENT FUEL. The temperature rise around the boundary of the main access corridors is less than 15°F above the ambient temperature. The boundary stresses and temperatures around the nearby waste corridors are shown in Figure 7-27. In both the waste and main access corridors, the boundary stresses do not exceed the limits for room and pillar stability criteria.

7.6 FAR FIELD ANALYSES

Two types of analyses were conducted to study the far field problems. These were: 1) a two-dimensional axisymmetric study of a circular shaped repository, and 2) a three-dimensional approximation using a semi-analytical method which modeled both square and rectangular shaped repositories. These studies were preceded by thermal analyses.

7.6.1 Thermal Analyses

The thermal analysis of the entire repository was undertaken by an axisymmetric finite difference program as described in volume Y/OWI/TM-36/19. The results from this thermal analysis were then input into the axisymmetric finite element program. The temperature distributions calculated by the finite difference program are illustrated in Figures 7-28 and 7-29 for HLW and SPENT FUEL at 190 kW/acre.

The semi-analytical program performed both the thermal and thermal stress calculations and was used since it could easily model the correct shape of the proposed repository.

7.6.2 Axisymmetric Analysis

The stresses and displacements in the medium surrounding a circular shaped repository were computed by an axisymmetric finite element program with thermal loading provided as input from the finite difference program.

The axisymmetric finite element mesh used for the Far Field calculations is shown in Figure 5-32 (the granite analyses). Since the form of the analysis required a complete computation of the thermal stress problem for each thermal loading, only a single analysis was computed at the expected time of maximum thermal strain energy. The maximum thermal strain energy was estimated to peak at 3000 yrs. for HLW and 7000 yrs. for SPENT FUEL in basalt (see volume Y/OWI/TM-36/19).

7.6.2.1 Surface Movements

The maximum surface displacements for HLW and SPENT FUEL at a thermal loading of 190 kW/acre calculated by the axisymmetric analysis are given below:

Waste Form	Time of Maximum Surface Movement	Maximum Surface Movement
HLW	3000 yrs	0.6 ft
SPENT FUEL	7000 yrs	1.9 ft

7.6.2.2 Estimated Changes in Permeability

Due to changes in normal stresses across pre-existing joints, the permeability of a rock mass can change substantially (see Figure 3-5). Thus changes in rock mass permeability would be caused by stress changes due to the excavation and thermal loading.

Results from the axisymmetric analysis show that tensile stresses exist in the θ direction, (i.e. perpendicular to the rz plane shown in Figure 5-32) from the ground surface to depths in excess of 500 feet. However, tensile stresses probably cannot be accommodated by an actual rock mass with joints because the pre-existing joints may open, increasing vertical permeability and load redistribution may occur. Since the axisymmetric analysis did not account for joints and a no-tension analysis was not undertaken, the only conclusion that can be reached from these studies is that the calculated tensile stress region provides only an approximation of the volume of rock that could be distressed.

It must be emphasized that the horizontal stress field for the generic conditions used in this analysis was assumed to be 1.5 times the vertical equivalent overburden pressure. It is possible that at some

sites the horizontal stress at shallow depths may be much greater than 1.5 times the vertical stress. This condition would reduce the changes in rock mass permeability that have been described in this section.

7.6.3 Semi-Analytical Studies

Two repositories were modeled by the semi-analytical method; one was square-shaped, the other had a shape more closely approximating the proposed design shape.

A plan view of the square repository is illustrated in Figure 7-30. It has the same plan area as that of a circular repository with a 10,000 ft diameter.

A plan view of the proposed rectangular shaped repository used in the preconceptual design studies is illustrated diagrammatically in Figure 7-31. There is a service zone in the center which contains access shafts and maintenance area. This service zone is straddled on two sides by areas of radioactive waste storage. Both problems modeled have symmetry with respect to both axes x and y . Therefore only one quarter of each problem was modeled directly.

7.6.3.1 Surface Movements

The calculated surface movements of a point at the center of the square repository (Figure 7-30), and a point located at approximately $y = 1500$ ft and $x = 0$ in the rectangular repository (see Figure 7-31) are illustrated in Figure 7-32 for both HLW and SPENT FUEL. These movements were calculated for a thermal loading of 190 kW/ acre. The points selected for study were the assumed positions of maximum displacement at any time, based on the analyses performed. The maximum surface displacements are as follows:

Waste Form	Repository	Time of Maximum Surface Movement	Maximum Surface Movement
HLW	Square	1000 yrs.	0.56 ft
	Proposed (Rectangle)	1000 yrs.	0.4 ft
SPENT FUEL	Square	7000 yrs.	2.4 ft
	Proposed (Rectangle)	7000 yrs.	1.7 ft

The large differences between the computed values of surface displacement from the finite difference/finite element axisymmetric analyses and the semi-analytical method of the proposed repository are apparently due to the differences in geometry. The maximum surface displacement for the proposed rectangular repository was only two thirds of the surface displacement of the square repository.

7.6.3.2 Thermal Profiles

Thermal profiles were computed for the proposed rectangular repository (Figure 7-31) using the semi-analytical method. The calculated thermal profiles at depths of 1000, 1450, 1800 and 2000 feet are illustrated in Figures 7-33, 7-34, 7-35 and 7-36 respectively for HLW at a thermal loading of 190 kW/acre and elapsed times of 500, 1000 and 3000 years. For these studies the assumed geothermal gradient was slightly greater than that used in the finite difference studies shown in Figure 7-28; however the calculated temperature rises are similar. For SPENT FUEL at a thermal loading of 190 kW/acre for elapsed times of 1000, 5000 and 10,000 years, the calculated thermal profiles at depths of 1000, 1450, 1800 and 2000 feet are illustrated in Figures 7-37, 7-38, 7-29, and 7-40 respectively. The calculated temperature rises above the geothermal temperature as shown in these figures are similar to those illustrated in Figure 7-29.

7.0 REFERENCES

1. Jaeger, J.C. and Cook, N.G.W., "Fundamental of Rock Mechanics", Chapman & Hall, London, 1971.

DEPTH
(FT)
SURFACE

DESCRIPTION

----- DASHED LINE INDICATES FLOW CONTACT

FIG. 7-1 GENERIC STRATIGRAPHIC SECTION - BASALT

FIG. 7-2 ASSUMED STRENGTH OF BASALT ROCK MASS WITH TEMPERATURE

FIG. 7-3 CROSS SECTION THROUGH HLW WASTE CORRIDORS IN BASALT

7-15

FIG. 7-4 CROSS SECTION THROUGH MAIN ACCESS CORRIDORS AND
HLW WASTE CORRIDORS IN BASALT

FIG. 7-5 CROSS SECTION THROUGH SPENT FUEL WASTE CORRIDORS IN BASALT

FIG. 7-6 CROSS SECTION THROUGH MAIN ACCESS CORRIDORS AND
SPENT FUEL WASTE CORRIDORS IN BASALT

FIG. 7-7 EXTENDED MESH WITH BOUNDARY CONDITIONS - MESH
EXTENDS TO GROUND SURFACE

FIG. 7-8 MESH PLOT FOR SIXTY FOOT PILLAR GEOMETRY
- AREA OF PLOTTED DATA FOR BASALT

FIG. 7-9 | TEMPERATURE CONTOUR PLOT FOR TOTAL RECYCLE
AT 5 YEARS - 190KW/ACRE IN BASALT

Temperatures in °F
Above Ambient

FIG. 7-10 TEMPERATURE CONTOUR PLOT FOR U ONLY RECYCLE
AT 5 YEARS - 190KW/ACRE IN BASALT

STRESS SCALE 1cm = 5000 psi

0 1 2 cm

In-situ Stress Field
Horizontal = 3000 psi
Vertical = 2000 psi

FIG. 7-11 STRESSES FOR TOTAL RECYCLE AT 5 YEARS-
190 KW/ACRE IN BASALT

FIG. 7-12 STRESSES FOR U-ONLY RECYCLE AT 5 YEARS-
190 KW /ACRE IN BASALT AND FIELD STRESSES

INSITU STRESS FIELD
 HOR = 3000psi
 VER = 2000psi

SCALES:

STRESSES 1cm REP 3000psi
 TEMP 1cm REP 90°F

0 1 2 cm

BOUNDARY STRESSES

PLOTTED EXCAVATION

TIME CANISTER
 PLACED (YRS)

0	0	0	0	0	0	0	0
---	---	---	---	---	---	---	---

BOUNDARY TEMPERATURES ABOVE AMBIENT

FIG. 7-13 BOUNDARY STRESSES AND TEMPERATURES OF INTERIOR WASTE CORRIDORS
 FOR IMMEDIATE CANISTER PLACEMENT - HLW 190KW/ACRES 5 YEARS
 FROM TIME LAST CANISTER WAS PLACED.

INSITU STRESS FIELD

HOR = 3000psi

VER = 2000psi

SCALES:

STRESSES 1cm REP 3000psi

TEMP 1cm REP 90°F

0 1 2 cm

PLOTTED EXCAVATION

TIME CANISTER
PLACED (YRS)

0	0	0	0	0	0	0	0
---	---	---	---	---	---	---	---

BOUNDARY STRESSES

BOUNDARY TEMPERATURES ABOVE AMBIENT

FIG. 7-14 BOUNDARY STRESSES AND TEMPERATURES OF EXTERIOR WASTE CORRIDOR
FOR IMMEDIATE CANISTER PLACEMENT - HLW - 190KW/ACRE 5 YEARS FROM
TIME LAST CANISTER WAS PLACED.

FIGURE 7-15 MESH PLOT FOR TWENTY FIVE FOOT PILLAR GEOMETRY
OF AREA FOR PLOTTED RESULTS

Temperatures are in °F
Above Ambient

FIG. 7-16 TEMPERATURE CONTOUR PLOT FOR SPENT FUEL
- 5 YEARS - 190 KW/ACRE - IN BASALT

STRESS SCALE 1cm = 5000 psi

FIG. 7-17 STRESSES FOR SPENT FUEL -5 YEARS-
190 KW/ACRE AND FIELD STRESSES IN BASALT

INSITU STRESS FIELD

HOR = 3000psi

VER = 2 000 psi

SCALES :

STRESSES 1 cm REP 3000psi

TEMP 1 cm REP 90°F

0 1 2 cm

CORRIDORS EXTEND OUTWARDS

TIME CANISTER
PLACED (YRS)

PLOTTED EXCAVATION

BOUNDARY STRESSES

BOUNDARY TEMPERATURES ABOVE AMBIENT

FIG. 7-18 BOUNDARY STRESSES AND TEMPERATURES OF INTERIOR WASTE
CORRIDORS FOR IMMEDIATE CANISTER PLACEMENT - SPENT FUEL
190KW/ACRE 5 YEARS FROM TIME LAST CANISTER WAS PLACED.

FIG. 7-19 TEMPERATURE CONTOUR PLOT FOR SPENT FUEL
25 YEARS - 100KW/ACRE

STRESS SCALE 1cm = 5000 psi

0 1 2 cm

Assumed Field Stresses:

Horizontal = 3000 psi

Vertical = 2000 psi

FIG. 7-20 STRESSES FOR SPENT FUEL AT 25 YEARS-
100 KW/ ACRE AND FIELD STRESSES IN BASALT

INSITU STRESS FIELD

HOR = 3000 psi

VER = 2000 psi

SCALES :

STRESSES 1 cm REP 3000 psi

TEMP 1 cm REP 90°F

0 1 2 cm

CORRIDORS EXTEND OUTWARDS

TIME CANISTER
PLACED (YRS)

↑ PLOTTED EXCAVATION

BOUNDARY STRESSES

BOUNDARY TEMPERATURES ABOVE AMBIENT

FIG. 7-21 BOUNDARY STRESSES AND TEMPERATURES OF INTERIOR WASTE CORRIDORS FOR IMMEDIATE CANISTER PLACEMENT - SPENT FUEL 100KW/ACRE
25 YEARS FROM TIME LAST CANISTER WAS PLACED.

INSITU STRESS FIELD
 HOR = 3000psi
 VER = 2000psi

SCALES:

STRESSES 1cm REP 3000psi

TEMP 1cm REP 90°F

0 1 2 cm

BOUNDARY STRESSES

BOUNDARY TEMPERATURES ABOVE AMBIENT

FIG. 7-22 BOUNDARY STRESSES AND TEMPERATURES OF INTERIOR WASTE
 CORRIDORS FOR CANISTER PLACEMENT SEQUENCE - HLW 190KW/ACRES 5 YEARS FROM TIME
 LAST CANISTER WAS PLACED.

INSITU STRESS FIELD

HOR = 3000 psi

VER = 2000 psi

SCALES:

STRESSES 1cm REP 3000psi

TEMP 1cm REP 90°F

0 2 cm

BOUNDARY STRESSES

BOUNDARY TEMPERATURES ABOVE AMBIENT

**FIG. 7-23 BOUNDARY STRESSES AND TEMPERATURES OF EXTERIOR WASTE CORRIDORS
FOR CANISTER PLACEMENT SEQUENCE - HLW 19CKW/ACRES 7 YEARS FROM TIME
LAST CANISTER WAS PLACED.**

FIG. 7-24 BOUNDARY STRESSES OF MAIN ACCESS CORRIDORS FOR CANISTER PLACEMENT SEQUENCE - HLW 190KW/ACRES 5 YEARS FROM TIME LAST CANISTER WAS PLACED.

FIG. 7-25 BOUNDARY STRESSES AND TEMPERATURES OF WASTE CORRIDORS
NEAR BY MAIN ACCESS CORRIDOR FOR CANISTER PLACEMENT SEQUENCE

- HLW 190KW/ACRE 5 YEARS FROM TIME LAST CANISTER WAS PLACED.

FIG. 7-26 BOUNDARY STRESSES OF MAIN ACCESS CORRIDORS FOR CANISTER PLACEMENT SEQUENCE - SPENT FUEL 100KW/ACRE 25 YEARS FROM TIME LAST CANISTER WAS PLACED.

CORRIDORS: EXTEND OUTWARD

WASTE CORRIDORS

MAIN ACCESS CORRIDORS

PLOTTED EXCAVATION

CANISTER PLACEMENT SEQUENCE

CANISTER PLACEMENT SEQUENCE

INSITU STRESS FIELD

HCR = 3000 psi

VER = 2000 psi

SCALE : STRESSES 1cm REP 3000psi

TEMP 1cm REP 90°F

0	1	2 cm
1	1	1

BOUNDARY STRESSES

BOUNDARY TEMPERATURES ABOVE AMBIENT

FIG. 7-27 BOUNDARY STRESS AND TEMPERATURES OF WASTE CORRIDOR NEAR BY
MAIN ACCESS CORRIDORS FOR CANISTER EMPLACEMENT SEQUENCE

-SPENT FUEL 100KW/ACRES 25 YEARS FROM TIME LAST CANISTER WAS PLACED.

FIG. 7-28 TEMPERATURES WITH DEPTH AT CENTER LINE OF AXISYMMETRIC REPOSITORY IN BASALT FOR HLW AT VARIOUS ELAPSED TIMES - 190KW/ACRE

FIG. 7-29 TEMPERATURES WITH DEPTH AT CENTER LINE OF AXISYMMETRIC
REPOSITORY

IN BASALT FOR SPENT FUEL AT VARIOUS ELAPSED TIMES - 190KW/ACRE

FIG. 7-30 | PLAN OF SQUARE UNDERGROUND WASTE REPOSITORY.

7-43

FIG. 7-31 PLAN OF PROPOSED RADIOACTIVE REPOSITORY

FIG. 7-32 MAXIMUM SURFACE DISPLACEMENT FOR HLW AND SPENT FUEL
FOR SQUARE AND PROPOSED REPOSITORIES WITH TIME IN BASALT

FIG. 7-33 : TEMPERATURE PROFILES AT A DEPTH 1000' FOR HLW AT
500, 1000 AND 3000 YEARS.

FIG. 7-34 TEMPERATURE PROFILES AT A DEPTH 1450' FOR HLW AT
500, 1000 AND 3000 YEARS.

FIG. 7-35 TEMPERATURE PROFILES AT A DEPTH 1800' FOR HLW AT
500, 1000 AND 3000 YEARS.

FIG. 7-36 TEMPERATURE PROFILES AT A DEPTH 2000' FOR HLW AT
500, 1000 AND 3000 YEARS.

FIG. 7-37 TEMPERATURE PROFILES AT A DEPTH OF 1000' FOR SPENT
FUEL AT 1000, 5000 AND 10,000 YEARS.

SECTION ALONG THE Y AXIS AS IN FIG. 7-31

FIG. 7-38 TEMPERATURE PROFILES AT A DEPTH OF 1450' FOR SPENT FUEL AT 1000, 5000 AND 10,000 YEARS.

SECTION ALONG THE Y AXIS AS IN FIG. 7-31

FIG. 7-39 TEMPERATURE PROFILES AT A DEPTH OF 1800' FOR SPENT FUEL AT 1000, 5000 AND 10,000 YEARS.

SECTION ALONG THE Y AXIS AS IN FIG. 7-31

FIG. 7-40 TEMPERATURE PROFILES AT A DEPTH OF 2000' FOR SPENT FUEL AT 1000, 5000 AND 10,000 YEARS.

TABLE 7-1 ROCK MASS PROPERTIES FOR A GENERIC BASALT

Type of Property	Parameter	Value	Customary English Unit
Index	. Unit Weight	180	lbs/ft ³
	. Natural moisture content	--	%
	. Porosity (Rock Mass)	0.6	%
Stress-strain	. Young's Modulus	1.8×10^6	lbs/in ²
	. Poisson's Ratio	0.26	---
Strength	. Strength Parameters		
	A	4.5	
	k	0.75	
Thermal	. Uniaxial Compressive Strength	18,000	lbs/in ²
	. Tensile Strength	0	lbs/in ²
	. Coefficient of Linear Thermal Expansion	3×10^{-6}	°F ⁻¹
	. Heat Capacity		BTU/lb-°F

TEMPERATURE

HEAT CAPACITY

32°F
212
392
572

0.17 BTU/lbs - °F
0.19
0.22
0.23

. Thermal Conductivity

TEMPERATURE

HEAT CAPACITY

32°F
122
212
302
392
572
752

0.65 BTU/hr-ft
0.69
0.73
0.76
0.79
0.85
0.90

Hydrological

. Horizontal permeability
. Vertical permeability

ft/yr
ft/yr

8.0 SUMMARY AND CONCLUSIONS

8.1 GENERAL

Based on the analyses described in this report, thermal loading guidelines were developed for the preconceptual design of radioactive waste repositories constructed in granite, shale and basalt rock units. Although quantitative results were calculated, the "generic" study concept, the restrictions in the scope of work and the lack of definitive information in certain areas dictate that the results should be taken in more of a general qualitative sense. Perhaps the most important functions that these "generic" type studies serve are to highlight the problems which will have particular significance in site specific studies and to indicate the directions that future studies should take.

8.2 THERMAL LOADING GUIDELINES

Canister and areal thermal loadings were selected which should not be detrimental to the environment, endanger the containment of the radionuclides or pose a threat to the safety of personnel during the operational life of the repository. To accomplish this, limits were set and analyses were completed on three different dimensional scales, Very Near Field, Near Field, and Far Field.

8.2.1 Very Near Field

The area within several feet of the canister was studied in the Very Near Field Analysis. The results indicated that within 1/2 year from the time of burial, fracturing of the rock adjacent to the canister would occur in all rock types for thermal loads as low as 1.2 kW/canister. Limits imposed by the scope of work and lack of data regarding rock behavior at high temperatures precluded analyses to calculate the exact extent of the fracturing. From past experience, it was assumed that fracturing would extend 6 inches into the rockmass, providing a thin, steel lining was installed into the storage borehole. Based on this assumption, additional thermal analyses were performed (Y/OWI/TM-36/19) to assure that waste and canister temperature limits were not exceeded. The results of these analyses are shown in Table 8-1.

8.2.2 Near Field

The stabilities of the repository rooms and pillars were evaluated in the Near Field studies. The calculated allowable thermal loadings which would satisfy stability criteria are listed in Table 8-2. The larger loadings allowed in granite and basalt can be attributed to the greater assumed strengths of these rock types in comparison to shale. Only spot rock bolting in localized areas of poor rock conditions would probably be required in granite and basalt. Continuous engineered support consisting of rock bolts and steel channels and mats would have to be used in shale. The values shown in Table 8-2 are from analysis in which an immediate canister placement was assumed. A comparative study indicated that these results are apparently more conservative than results from analyses in which a sequenced canister placement was assumed.

8.2.3 Far Field

The region analyzed in the Far Field studies included the rock mass extending vertically from the repository area up to the ground surface and horizontally from the center of the repository out to the outer controlled area boundary, three miles away. Movements, temperatures and stresses within this zone were calculated for the thermal loadings shown in Table 8-2. The calculated maximum ground surface uplifts and the approximate times at which they occur are listed in Table 8-3. All displacements are within the preliminarily assumed limit of 4 feet. Computed temperature rises at the ground surface never exceeded 1°F. Maximum temperature rises above ambient of approximately 350°F for granite and shale and 300°F for basalt were calculated at the repository level for SPENT FUEL. For HLW, the temperature rises in the repository area were calculated to be about 250°F for granite and 200°F for shale and basalt. The stress analyses indicated that large volumes of rock above the repository may be destressed. These zones extend from the ground surface down to depths of 1000 ft. in granite, 200 ft. in shale and 500 ft. in basalt.

8.3 LIMITATIONS AND ESTIMATED UNCERTAINTIES OF RESULTS

The allowable thermal loadings and calculated rock responses discussed in Section 8.2 should be accepted as approximate values only. The degree of uncertainty is related to the assumptions that were used for site geology and rock properties, and to the limitations of the analytical methods that were employed.

8.3.1 Variances of Site Geology

It is most likely that the exact site geological conditions and stratigraphies at the actual repository sites will be different than those assumed in this preconceptual generic study. This is particularly true for the bedded deposits, shale and basalt, where the formation thicknesses, and bedding sequences will undoubtedly vary from those selected for these precursory studies. The results of the Far Field studies would be effected by these variations.

8.3.2 Variances in Rock Properties

Variations in the assumed engineering and thermal properties of rock may have important effects on the results of analyses. The values assumed for these studies were carefully selected to be representative of the rock types investigated. However, the literature review performed in conjunction with the analyses indicated that wide ranges of values of specific properties occur for the same rock type. The results of the Near Field studies of room and pillar stability would be particularly effected by any variations in these properties. A summary of the qualitative changes in the calculated Near Field thermal loadings related to changes in rock properties or assumed conditions follows:

<u>Change in Generic Rock Conditions/Properties</u>		<u>Safe Thermal Loading for Near Field Criteria</u>
Horizontal in-situ stress		
field -	decreased	increased
-	increased	decreased
Young's modulus	- decreased	increased
	- increased	decreased

Coefficient of linear thermal expansion -	decreased	increased
-	increased	decreased
Rock Mass Strength		
-	increased	increased
-	decreased	decreased

Another major uncertainty involving predicted rock behavior pertains to the lack of existing information regarding the effects of temperature on rock mass properties. These effects were neglected or arbitrary relationships were assigned for the studies described in this report.

8.3.3 Limitations of Analytical Studies

Time permitted only relatively simplistic analytical studies to be performed. The complex interaction between heat applied, rock movements and ground water flows had to be analyzed by decoupled models. Coupling might produce results different than those described in this report.

Perhaps one of the most important limitations occurred because time did not allow enough iterations between the rock stress analyses and the ground water flow studies. Only one thermal loading, that determined by Near Field considerations, was modeled in the ground water flows (Y/OWI/TM-36/21). The results indicated that certain radionuclides would migrate from the repository area in concentrations greater than allowed by present day standards. It is possible that ground water analyses using lower thermal loadings would have resulted in determining a thermal loading at which migration would not be a problem. Accordingly, this possible lower allowable thermal loading would have overridden the Near Field allowable thermal loading which was used in all other aspects of the preconceptual design efforts.

8.4 AREAS OF ADDITIONAL WORK

During the course of the studies described in the report, it became apparent that there were several areas of study where additional work will be required prior to realization of a comprehensive design of a

repository in granite, shale or basalt. It should be pointed out, however, that much of this work is currently underway in many areas of the United States and abroad. Answers to several of the questions will be available in the near future.

8.4.1 Laboratory and Field Tests

The following laboratory and field test are expected to provide data needed for assessing the proposed repository behavior.

Laboratory:

- o Intact and large blocks (containing a number of fractures) to be tested to determine Young's modulus, coefficient of linear thermal expansion, conductivity, fissure permeability, and strength with respect to changes in temperature and pressure.

Field:

- o Tests of lined and unlined canister boreholes under thermal loading. The canister lining and rock temperatures, the degree and extent of any fracturing, and the overall performance of the lined or unlined borehole should be monitored. These tests should be conducted in a full-scale canister borehole.
- o Tests of a complete excavation under high thermal loading to give rise to material failure around the excavation. Until the rock has been tested to the stage of instability, the stability of rooms and pillars predicted from numerical studies cannot be relied upon. Throughout these field tests, temperatures, displacements, and stresses should be monitored.
- o In-situ stress field will need to be measured at potential repository sites.

8.4.2 Numerical Analysis

The recommendations for additional work on the numerical analysis of a repository in granite include:

- o coupling of thermo-mechanical and ground water flow analyses
- o inclusion of the behavior of major joints
- o no-tension analysis for the Far-Field case
- o behavior of fractured rock around a lined canister borehole

TABLE 8-1

ACCEPTABLE CANISTER THERMAL LOADS

<u>WASTE TYPE</u>	<u>THERMAL LOAD/CANISTER IN kW</u>		
	<u>GRANITE</u>	<u>SHALE</u>	<u>BASALT</u>
Vitrified Glass HLW	1.7	1.2	1.3
Calcined HLW	1.6	1.1	1.1

TABLE 8-2

ACCEPTABLE NEAR FIELD THERMAL LOADINGS

<u>WASTE FORM</u>	<u>RETRIEVABLE PERIOD</u>	<u>ACCEPTABLE NEAR FIELD THERMAL LOADS, kW/ACRE</u>		
		<u>GRANITE</u>	<u>SHALE</u>	<u>BASALT</u>
HLW	5 years	190	120	190
SPENT FUEL	5 years	190	120	190 ^b
SPENT FUEL	25 years	100 ^a	55	100 ^a

- NOTES: a. Initial estimations of 80 kW/acre were provided for other aspects of repository design studies. Time did not permit redesign based on these final figures.
- b. The basalt repository design is based on this limit; however, later analyses (Y/OWI/TM-36/19) indicate that the controlling factor might be the spent fuel cladding temperature and that the acceptable Near Field thermal loading might be as low as 115 kW/acre for 5-year retrievability.

TABLE 8-3

CALCULATED MAXIMUM SURFACE UPLIFTS

<u>ROCK TYPE</u>	<u>WASTE FORM</u>	<u>MAXIMUM UPLIFT, IN FEET</u>	<u>TIME OF MAXIMUM UPLIFT, IN YEARS</u>
Granite ¹	HLW	0.7	500
	SURF	1.9	2000
Shale ²	HLW	0.5	700
	SURF	1.7	3000
Basalt ¹	HLW	0.4	1000
	SURF	1.7	7000

- NOTES: 1. Assuming DEPTH OF REPOSITORY AT 2000 FT. AND A THERMAL LOADING OF 190 kW/ACRE.
2. Assuming DEPTH OF REPOSITORY AT 1500 FT. AND A THERMAL LOADING OF 120 kW/ACRE.

APPENDIX A

CHECK ON ACCURACY OF FINITE-ELEMENT AND BOUNDARY-ELEMENT PROGRAMS

A.1 CHECK ON ACCURACY OF FINITE-ELEMENT PROGRAM

A.1.1 Check on Program Accuracy

Although the computer program SAP4⁽¹⁾ used in the present study, see Section 2.2.4.1 for a more complete description, is well documented and widely used, two simple checks (plane-strain and axisymmetric problems) were undertaken to verify the accuracy of the program.

The stresses and deformations of a hollow cylinder in plain strain under a linear radial temperature gradient were computed using SAP4. The geometry of the problem, temperature distribution, and the plane-strain finite-element mesh are illustrated in Figure A-1. The linear radial temperature distribution varied from 10°C to 20°C. A reference temperature at which no thermal stress occurs was inputted as 10°C. The problem was represented by 10 plane-strain finite elements (consisting of four constant-strain triangular elements) in the radial direction, as shown in Figure A-1. All element nodes are free to move in the r direction but are fixed in the θ direction. The dimensions of the hollow cylinder and material properties used are all quoted in Figure A-1.

The SAP4 results, radial stress and displacement are presented in Figure A-2 together with values from the analytical solution.⁽²⁾ From the graphical results it is clear that the SAP4 results and values from the analytical solution are in very close agreement.

An identical problem to that shown in Figure A-1 was analyzed by an axisymmetric finite-element representation using SAP4. The geometry of the hollow cylinder, its temperature distribution, and the axisymmetric finite-element mesh consists of a single row of 10 elements in the radial direction. All element nodes are free to move in the r direction but are fixed in the z direction. The temperature distribution is the same as shown in Figure A-1, as was the reference temperature. The problem dimensions and material properties are quoted in Figure A-3.

The SAP4 and analytical results, radial stress, and displacement are tabulated in Table A-1 and are identical (to plotting accuracy) to those presented in Figure A-2 for the plane-strain analysis. It is clear that the SAP4 results and values from the analytical solution are in very close agreement.

A.1.2 Check on Accuracy of Mesh Size and Boundary Conditions

The finite-element mesh initially used for the stress analysis of the near-field geometry in plane strain is illustrated in Figure A-4a. The elements constituting the canister and plug were given low values for elastic parameters for temperature loading analyses considered in this section. That is, a trench was modelled down the centerline of the corridor. This geometry was considered only in this section and not elsewhere. In Figure A-4b the mesh near the excavation and canister has been expanded. All plotted data are displayed only in the area illustrated in Figure A-4b. Two different boundary conditions designated as A and B for the finite-element mesh are shown in Figure A-5. The only difference between boundary conditions A and B is the vertical fixing of the uppermost nodes of the mesh. The reason for doing this was to determine what difference in stresses would occur under thermal loading between cases A and B. The two cases A and B were chosen because they straddle the real case, i.e., elements extending all the way to the free surface.

The temperature contours supplied by SAI (Y/OWI/TM-36-19) for an areal thermal loading of 120 kW acre at an elapsed time of 5 years after emplacement of Uranium and Plutonium recycle waste in granite are shown in Figure A-6. A thermal stress analysis of the nearfield geometry for the two boundary conditions A and B was undertaken for planestrain conditions. The stresses due to the above temperature distribution for granite rock-mass properties as quoted in Section 5.2, are shown in Figures A7 and A8 for boundary conditions A and B, respectively. From a close examination of these two plots it is clearly apparent that the stresses for the two cases A and B differ significantly in the area of the sidewalls of the excavation and in the pillar. The variance (in particular, the vertical stress in this area) is because of the large difference in allowed material expansion for boundary conditions A and B.

Because of the large differences in computed stress for the two analyses with different boundary conditions, it was considered prudent to extend the mesh in order to analyze the real situation more accurately. The original mesh is shown in Figure A-9a. The enlarged mesh (extending from the free surface, 2000 feet above the excavation, to a depth of approximately 1000 feet below the repository) is illustrated in Figure A-9b. The boundary conditions for this extended mesh (rollers along lines of symmetry, fixed lower surface and free upper surface) are also shown in Figure A-9. The stresses due to the temperature distribution shown in Figure A-6 with the same granite rockmass properties used previously are illustrated in Figure A-10 for the extended mesh. The stresses shown in Figure A-10 for all elements lie between the two previous cases, i.e., boundary conditions A and B shown in Figures A-7 and A-8.

Since there are large differences in computed stresses for the two boundary conditions A and B compared with the extended mesh, it was decided that the extended mesh be used for all thermal loading analyses of near field geometry.

A.1.3 Check on Accuracy of Element Density

In order to check whether the element density is sufficient for the near-field geometry, plane-strain analyses of the excavation for a unit vertical stress field were undertaken. The vertical stresses at mid-height of the pillar for the mesh shown in Figure A-9, (as calculated by the finite element method, and previous numerical results using the boundary element method³) are shown in Figure A-11. Since there is close agreement between the two results, the element density around the excavation was considered to be adequate.

A.2 BOUNDARY-ELEMENT PROGRAMS

A.2.1 Boundary-Element Program for Near-Field Analysis

The boundary-element program used in these studies, was originally developed by Bray³, and modified to compute displacements.⁴ More recently, using the solution of a line heat source by Hart⁵, it was adapted to solve problems of transient thermo elasticity.⁶ The method consists of the fictitious force type and is at present limited to homogeneous isotropic media. The method involves finding a distribution of singularities (in

this case, strip loads) around the boundary to solve the particular problem. Firstly, the problem of in-situ stress field at infinity and excavating an excavation is analyzed; secondly, the stresses and temperatures at any point in the medium on the boundary of the excavation are computed; and finally, the distribution of singularities is altered to remove any normal and surface tractions on the boundary due to the presence of the heat sources. The most significant assumption in the present program is that the air in the corridors is assumed to have the same thermal properties as the host rock. The errors involved in this assumption are illustrated with a comparison of results to those computed previously by finite difference for thermal analyses and finite elements for thermal stress analysis.

A.2.1.1 Check on Program Accuracy

The program analyzes two-dimensional plane problems, and a simple check on accuracy was undertaken of a circular hole in an infinite medium in a uniaxial stress field, Figure A-12. The circumferential stresses computed by the program with nine (9) boundary elements to represent one quadrant of the problem are tabulated in Table A-2 along with those determined by the analytical solution.² It is apparent that the agreement is very close, which should be expected, since the method solves the problem on the boundary.

A.2.1.2 Check on Accuracy of a Single Replacing Multiple Line Heat Sources

In order to reduce computational efforts, a check was undertaken of the possibility of replacing multiple-line heat sources by a single line heat source to represent waste canisters. The case of a single circular tunnel in an infinite medium was chosen for the analysis. The circular tunnel with a single line heat source is shown in Figure A-13a while the circular tunnel with three line heat sources is shown in Figure A-13b. The boundary stresses and temperatures for these two cases, Figures A-13a and A-13b, for an HLW canister placed for 5 years are tabulated in Table A-3. As shown in Table A-3, there exists close agreement of both temperatures and stresses for the two solutions; therefore, it was considered satisfactory to represent the waste canister by a single line heat source.

A.2.1.3 Check on Accuracy of Thermal Stress Analysis

The solution of a line heat source in an infinite homogeneous medium has been checked previously.⁵ However, a check was warranted regarding the assumption that the air in the corridor had the same thermal properties as the host rock.

The thermal stress analysis of an infinite number of excavations with waste canisters installed has been computed by finite difference for thermal analysis, (volume Y/OWI/TM-36-19) and by the finite element method for the thermal stress analysis for granite. For the boundary element analyses the thermal output of the canisters was modelled as a single exponentially decaying heat source as given in equation (A.1):

$$Q = Q_0 e^{-t\lambda} \quad (A.1)$$

where Q is the strength of the source at time t
 Q_0 is the strength of the source at time $t = 0$
 t is the time
and λ is the decay constant.

The numerical approximate, and true power outputs for HLW and SPENT FUEL are illustrated in Figure A-14 for a 5 year storage period. The results for SPENT FUEL for 25 years storage is illustrated in Figure A-15. As depicted in Figures A-14 and A-15, the numerical model of the true heat source is shown to be in close agreement for the cases of HLW and SPENT FUEL for both five and twenty five year storage periods.

The boundary stresses and temperatures were computed by the Boundary element (B.E.) and finite difference/finite element (F.D./F.E.) methods. The results, together with the excavation geometry are shown in Figure A-16. The results are in good agreement along the boundary of the excavation except in the floor. Here the temperatures calculated by the B.E. method are higher than those calculated by the F.D./F.E. method. The thermal stresses in the floor have not been shown for the F.D./F.E. method but were less than for the B.E. method. In the F.D./F.E. analyses, ditches near the sidewalls were modelled. This difference in geometry apparently resulted in differences in the calculated results for floor temperatures and stresses. However, the agreement between the results of the F.D./F.E. and B.E. methods is reasonably close for all other areas.

Therefore, it was considered satisfactory to compute thermal stresses from the B.E. method for design purposes.

A.3 SEMI-ANALYTICAL PROGRAM FOR FAR-FIELD ANALYSIS

The program used was the semi-analytical one of St. John⁷, which does not involve the reduction of a system of equations but merely the application of shear tractions at the force surface to remove shear stresses generated midway between a source and a sinkpoint heat source. The program was modified to allow sources and sinks to be placed in a time sequence for the calculation of stresses, displacements, and temperatures around the shafts and service areas for the working life of the repository. For the thermalstress analysis for large elapsed times, immediate canister placement was assumed.

The thermal output of the canisters was modelled as a number of exponentially decaying heat sources each having a strength-decay curve as given by equation (A.1). The HLW thermal output was modelled by the supposition of seven such sources. The relevant strength and decay constants for these sources are given in Table A-4. The strengths of these sources were modified depending on the thermal loading and the area each source represented.⁷ For the case of SPENT FUEL, six sources were used to model its thermal output. The strengths and decay constants for these sources are listed in Table A-5. Again these strengths are modified for thermal loading and area as mentioned for the HLW case. The above mentioned representation of HLW and SPENT FUEL thermal outputs are in close agreement with the predicted thermal outputs of such waste forms as shown in Table A-6. It should be noted that the constants shown in Table A-4 and A-5 and the values shown in Table A-6 are for slightly different forms of waste than those described in other volumes of this document. However, the differences are minor and would have no significant effects on the results presented here or in the other volumes.

REFERENCES TO APPENDIX A

1. Bathe, K.J., Wilson, E.L., and Peterson, F.E., SAP4 "A Structural Analysis Program for Static and Dynamic Response of Linear System", Report No. EERC73-11 Rev. April 1974, University of California, Berkeley.
2. Timoshenko, S. and Goodier, J.N., "Theory of Elasticity", McGraw-Hill (N.Y.), 1970.
3. Bray, J.W., "A Program for Two-Dimensional Stress Analysis using the Boundary Element Method", Rock Mechanics Progress Report No. 16, Rock Mechanics Project, Imperial College, London, 1976.
4. Hocking, G., "BEM8A - J.W. Bray's Boundary Element Program Updated to Calculate Displacements", Rock Mechanics Progress Report No. 17, Rock Mechanics Project, Imperial College, London, 1976.
5. Hart, G., Ph.D. Thesis in Preparation, University of Minnesota, Minnesota, 1977.
6. Hocking, G., "Boundary Element Program for Analysis of Approximate Transient Thermo-Elasticity", Dames & Moore Technical Note No. 12, 1978.
7. St. John, C.M., "Thermo-elastic Analysis of Spent Fuel and High Level Radioactive Waste Repositories in Salt - a Semi-Analytical Solution", Report submitted to Office of Waste Isolation, Union Carbide Corporation - Nuclear Division, Y/OWI/SUB-7118/1, 1977.

HOLLOW CYLINDER

LINEAR RADIAL TEMPERATURE DISTRIBUTION

MATERIAL PROPERTIES

$\nu = 0.25$

$E = 10^{10} \text{ psi}$

$\alpha = 10^{-2} (^{\circ}\text{C})^{-1}$

NOTE:-
PROGRAM IS INDEPENDENT OF
MAGNITUDE OF MATERIAL
PROPERTIES

PLANE STRAIN FINITE ELEMENT REPRESENTATION

FIG. A-1 HOLLOW CYLINDER WITH LINEAR TEMPERATURE
GRADIENT - PLANE STRAIN

FIG. A-2
 COMPARISON OF FINITE ELEMENT AND ANALYTICAL SOLUTIONS
 PLANE STRAIN

HOLLOW CYLINDER

MATERIAL PROPERTIES

$$\begin{aligned} \nu &= 0.25 \\ E &= 10^{10} \text{ (psi)} \\ \alpha &= 10^{-2} (\text{°C})^{-1} \end{aligned}$$

NOTE :

PROGRAM IS INDEPENDENT OF MAGNITUDE OF MATERIAL PROPERTIES

LINEAR RADIAL TEMPERATURE DISTRIBUTION

AXISYMMETRIC FINITE ELEMENT REPRESENTATION

FIG. A-3

HOLLOW CYLINDER WITH LINEAR TEMPERATURE GRADIENT
- AXISYMMETRIC

FIG. A-4 MESH PLOT A) PARTIAL MESH AND
B) MESH OF AREA FOR PLOTTED RESULTS.

FIG. A-5 BOUNDARY CONDITIONS A) FREE AND B) FIXED AT TOP BOUNDARY.

CONTOURS IN 60° F INCREMENTS
ALL TEMPERATURES ABOVE AMBIENT

FIG. A-6 TEMPERATURE DISTRIBUTION 1-120KW/ACRE
AT 5 YEARS FOR HLW

FIG. A-7 STRESSES FOR TEMPERATURE DISTRIBUTION 1. FOR
BOUNDARY CONDITION A-120KW/ACRE
AT 5 YEARS FOR HLW-FREE TO BOUNDARY.

FIG. A-8 STRESSES FOR TEMPERATURE DISTRIBUTION
1. FOR BOUNDARY CONDITION B.-120KW/ACRE
AT 5 YEARS FOR HLW-FIXED TOP BOUNDARY.

FIG. A-9 EXTENDED MESH WITH BOUNDARY CONDITIONS - MESH
EXTENDS TO THE GROUND SURFACE

0 2cm

STRESS SCALE 1cm. = 2400 psi.

FIG. A-10 STRESSES FOR TEMPERATURE DISTRIBUTION
1. FOR EXTENDED MESH CONFIGURATION
-120KW/ACRE AT 5 YEARS FOR HLW.

FIG. A-11 VERTICAL STRESSES IN MID-HEIGHT OF PILLAR
FOR A UNIT VERTICAL STRESS FIELD

A-19

FIG. A-12 CIRCULAR TUNNEL IN A UNIAXIAL STRESS FIELD.

FIG. A-13 SINGLE CIRCULAR TUNNEL WITH CANISTER MODELLED BY
A) SINGLE LINE HEAT SOURCE AND B) MULTIPLE HEAT SOURCE.

FIG. A-14 HLW AND SPENT FUEL POWER DECAY WITH TIME FOR 5 YEARS.

FIG. A-15 SPENT FUEL POWER DECAY WITH TIME FOR 25 YEARS.

FIG. A-16 COMPARISON OF BOUNDARY STRESSES AND TEMPERATURES FOR THE
 B.E. AND F.D./F.E. METHODS - HLW 190KW/ACRES AT 5 YEARS IN GRANITE.

TABLE A-1

COMPARISON OF AXISYMMETRIC FINITE ELEMENT AND ANALYTICAL SOLUTIONS

ELEMENT NO.	1	2	3	4	5	6	7	8	9	10		
$\sigma_r / \left(\frac{E}{1-\nu} \right)$	0.258	0.535	0.777	0.848	0.839	0.769	0.653	0.500	0.319	0.115	finite element analytical	
	0.274	0.534	0.767	0.839	0.831	0.761	0.645	0.493	0.313	0.109		
NODE NO.	1	2	3	4	5	6	7	8	9	10	11	
Displacement at node	0.069	0.068	0.069	0.072	0.077	0.084	0.092	0.102	0.113	0.125	0.139	finite element analytical
U (inches)	0.069	0.068	0.070	0.073	0.078	0.084	0.092	0.102	0.113	0.125	0.139

TABLE A -2

CIRCUMFERENTIAL STRESSES AROUND A CIRCULAR TUNNEL IN A UNIAXIAL STRESS FIELD AS IN FIGURE A-12

	θ	0^0	10^0	20^0	30^0	40^0	50^0	60^0	70^0	80^0	90^0
Boundary Element Method	$\sigma_{\theta\theta}$	-1.00	-0.88	-0.53	0.01	0.65	1.35	2.00	2.53	2.88	3.00
Analytical	$\sigma_{\theta\theta}$	-1.00	-0.88	-0.53	0.00	0.65	1.35	2.00	2.53	2.88	3.00

TABLE A-3

COMPARISON OF CIRCUMFERENTIAL THERMAL STRESSES AND TEMPERATURES AROUND A CIRCULAR TUNNEL
DUE TO SINGLE AND MULTIPLE LINE SOURCES TO REPRESENT A CANISTER AS IN FIGURE A-13

	θ	0^0	30^0	60^0	90^0	120^0	150^0	180^0
Multiple Line	$\sigma_{\theta\theta}$ (psi)	0.64	0.57	0.65	1.02	1.01	0.37	0.06
Sources	T (^0C)	62.9	55.5	44.9	37.1	32.1	29.3	28.4
Single Line	$\sigma_{\theta\theta}$ (psi)	0.62	0.55	0.66	1.02	1.01	0.37	0.06
Sources	T (^0C)	61.7	55.0	44.7	36.9	31.9	29.2	28.3

Table A-4 Strengths and Decay Constants for Modelling HLW (7)

<u>Strengths</u>	<u>Decay Constants</u>
(Q_0)	(λ)
0.255	1.5×10^{-5}
0.65	7.49×10^{-5}
2.97	1.12×10^{-3}
7.13	2.34×10^{-3}
849.8	2.42×10^{-2}
77.59	1.17×10^{-1}
64.71	4.83×10^{-1}

Table A-5 Strengths and Decay Constants for SPENT FUEL (7)

<u>Strengths</u>	<u>Decay Constants</u>
(Q_0)	(λ)
9.0	2.3×10^{-5}
17.98	9.95×10^{-5}
167.06	1.75×10^{-3}
805.49	2.16×10^{-2}
60.0	4.014×10^{-2}
130.0	2.915×10^{-1}

TABLE A-6

Computed and tabulated power generations (7)

Time after reprocessing (Years)	Spent Fuel		High Level Waste	
	Calculated (Watts)	Tabulated (Watts)	Calculated (Watts)	Tabulated (Watts)
10	1189.5	1189.0	1003.1	1003.1
11	1136.8	1136.6	949.4	951.3
12	1092.8	1091.2	906.6	908.6
13	1055.4	1054.9	871.1	873.0
14	1023.2	1023.6	840.3	841.4
15	994.8	996.4	812.9	812.9
16	969.5	972.2	787.9	787.9
17	946.5	949.1	764.7	764.1
18	925.3	928.9	742.9	742.7
19	905.6	908.8	722.2	721.4
20	887.1	890.7	702.6	702.2
25	806.5	808.3	615.3	615.6
30	738.1	739.2	541.8	542.0
40	624.4	624.4	423.9	423.9
100	286.1	288.5	105.6	105.8
200	159.7	162.9	16.4	16.9
300	128.5	128.9	7.4	7.6
500	96.9	95.7	4.9	5.0
1000	54.6	55.4	2.5	2.7
5000	19.0	18.8	0.7	0.7
10000	13.8	13.8	0.5	0.5
25000	6.6	6.7	0.3	0.2
50000	3.0	3.0	0.1	0.1
100000	0.9	1.1	0.1	0.1