WPO 42835

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CALCULATION SHEET

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Calculation No. A141-GE-07
Project Title Rock Mechanics Analysis of SMC
Made by Marc C. Loken and Rui Chen
Contract No. 4060/A141
Date January 11, 1994
Subject Rock Mechanics Analysis of SMC
Checked by
Ref. Dwgs.
Date

ROCK MECHANICS ANALYSIS OF SMC

1.0 INTRODUCTION

The objective of this analysis is to determine the magnitude and time duration of the expected loads imposed on the concrete emplacement. These loads may approach (or even exceed) the magnitude of the preexisting stress level at the test facility (~ 15 MPa) because of the following factors:

- The confined thermal expansion of the concrete as it heats up during hardening (due to its heat of hydration).
- The inward creep of the surrounding salt toward the excavated drift and the restraint to such creep provided by the concrete.
- The stress concentrations that result at the ends of the concrete emplacement.

An assessment of these loads will be made in light of the specified design strength of the concrete and ultimately will be used to determine the adequacy of the emplacement designs.

Another objective of this analysis is to determine the potential for thermal cracking of the SMC. Thermal cracking of mass concrete is caused by bonding of frictional forces between the concrete and the surrounding salt or underlying lifts. The degree of external restraint depends on the stiffness and strength of the concrete and restraining material and on the geometry of the emplacement. Internal restraint is caused by temperature gradients within the concrete itself. The degree of internal restraint depends on the quantity of heat generated, the thermal properties of the concrete, and the thermal boundary conditions.

Both material and design parameters may be controlled to limit thermal cracking. Material parameters include:

- Heat of hydration of the concrete.
- Thermal properties of the concrete, including coefficient of thermal expansion and thermal diffusivity.
- Age-dependent mechanical properties of the concrete, including strength, moduli, and creep.
- Shrinkage of the concrete.

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Design parameters include:

- Emplacement geometry, including concrete thickness, length, and end conditions.
- Lift dimensions (mass quantity).
- Time between placement of lifts.
- Concrete mixing temperature.
- Surrounding rock temperature.
- Artificial cooling.

2.0 DESIGN CONSTRAINTS

The design compressive strength in the concrete is specified to be 4,500 psi at 180 days.

3.0 DESIGN ASSUMPTIONS

Several simplifying assumptions were made in performing this analysis, including:

1. Uniform initial temperature = 27°C.
2. Homogeneous domain; i.e., the vertical stratigraphy is neglected.
3. Equivalent axisymmetric room; i.e., the stress concentrations at corners are neglected.
4. Average density of overburden material (ρ_{ave}) is assumed to be 2,270 kg/m^3.
5. Uniform, lithostatic initial stress field (i.e., $\sigma_r = \sigma_\theta = \sigma_z$).
6. Depth is 656 m (2,150 ft).
7. Design life of emplacement = 50 yrs.
8. Time of emplacement of the concrete emplacement is 1 yr after the room has been excavated.
9. Stiffness of concrete is assumed to be age-dependent, increasing from zero at time of emplacement to its intact value at time of maximum SMC temperature; i.e., at 0.02 yrs (175 hrs) after emplacement.
10. Inelastic behavior (yielding or cracking) is not considered in this analysis because of lack of criteria.

4.0 FINDINGS AND CONCLUSIONS

A number of conclusions can be drawn from the calculation:

1. Stress concentrations (singularities) occur at the ends of the emplacement at the salt interface.
2. The stresses within the SMC increase as the length of the emplacement decreases.
3. The radial stresses that develop near the ends of the emplacement may cause some localized crushing.
4. The shear stresses and axial tensile stresses that develop near the ends of the emplacement indicate a potential for localized cracking (yielding) of the concrete.

5.0 INPUT PARAMETERS

5.1 Problem Geometry

The room is assumed to be 20 ft (6.1 m) in width (W) and 12 ft (3.66) m in height (H). The radius of the equivalent axisymmetric room is calculated as $R = (WH/\pi)^{1/2} = 2.66$ m. Emplacement lengths of 20 ft (6.1 m) and 6 ft (1.83 m) were investigated.

5.2 Material Properties

5.2.1 Salado Mass Concrete (SMC) — Linear Elastic

Elastic Modulus: $E = 4.3(10^6)$ psi = 29.6 GPa [Wakeley et al., 1993]

Poisson's Ratio: $\nu = 0.19$ [Van Sambeek, 1987]

Coefficient of Thermal Expansion: $\alpha = 11.9(10^{-6})/°C$ [Wakeley et al., 1993]

5.2.2 Clean Halite [Bailey et al., 1992]

5.2.2.1 Linear Elastic

Elastic Modulus: $E = 31$ GPa

Poisson's Ratio: $\nu = 0.25$

Coefficient of Thermal Expansion: $\alpha = 45(10^{-6})/°C$

5.2.2.2 Munson-Dawson Creep

Table 5-1. Parameter Set From Bailey et al. [1992] (Adapted From Munson et al. [1989])

Elastic Properties	
μ	12.4 GPa
E	31.0 GPa
ν	0.25

Creep Properties			
Parameters	**Clean Salt**	**Argillaceous Salt**	**Units**
A_1	8.386 E22	1.407 E23	/s
Q_1	25000	25000	cal/mol
n_1	5.5	5.5	
B_1	6.086 E6	8.998 E6	/s
A_2	9.672 E12	1.314 E13	/s
Q_2	10000	10000	cal/mol
n_2	5.0	5.0	
B_2	3.034 E-2	4.289 E-2	/s
σ_0	20.57	20.57	MPa
q	5.335 E3	5.335 E3	
m	3.0	3.0	
K_0	6.275 E5	2.470 E6	
c	0.009198	0.009198	/T
α	−17.37	−14.96	
β	−7.738	−7.738	
δ	0.58	0.58	

5.3 Initial Conditions

The uniform initial temperature is assumed to be 27°C (300 K). The initial, uniform lithostatic stress distribution at a depth of 656 m is assumed to be $\sigma_z = \sigma_r = \sigma_\theta = 14.9$ MPa.

(656)(0.0227) = 14.89 MPa

6.0 MODELING CONSIDERATIONS

An axisymmetric representation of the room, the emplacement, and the surrounding halite is shown in Figure 6-1. The left vertical boundary is the axis of rotation at the center of the room along its length. The lower horizontal boundary is a plane of symmetry located at the midlength of the concrete emplacement. The normal displacements along these two boundaries are zero. The upper horizontal and right vertical boundaries are at the same location as those used in the thermal analyses and are beyond the mechanical influence of the excavation of the room, placement of the concrete, and subsequent creep of the halite through the simulation period of 50 yrs. The upper horizontal boundary is modeled as a "no-normal displacement" boundary. Using the previously calculated temperature fields as input conditions [Loken, 1993], the displacements and stresses were calculated using the finite element program **SPECTROM-32** [Callahan et al., 1990]. Eight-noded, quadrilateral finite elements were used for all materials. All computer programs used in this analysis are listed in Table 6-1.

Table 6-1. Computer Programs Used

Computer Code	Version
FASTQ	3.0
SPECTROM-32	4.05
ALGEBRA	1.08
BLOT	1.01.1

6.1 Modeling Sequence

The rock mechanics analysis consisted of the following modeling sequence:

1. Instantaneous excavation of the room at time = 0. redistributed ?
2. Isothermal creep of salt for 1 yr to establish the preexisting stress state in the salt surrounding the room.
3. Emplacement of heat-generating SMC at 1 yr with zero stiffness.

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Date January 11, 1994

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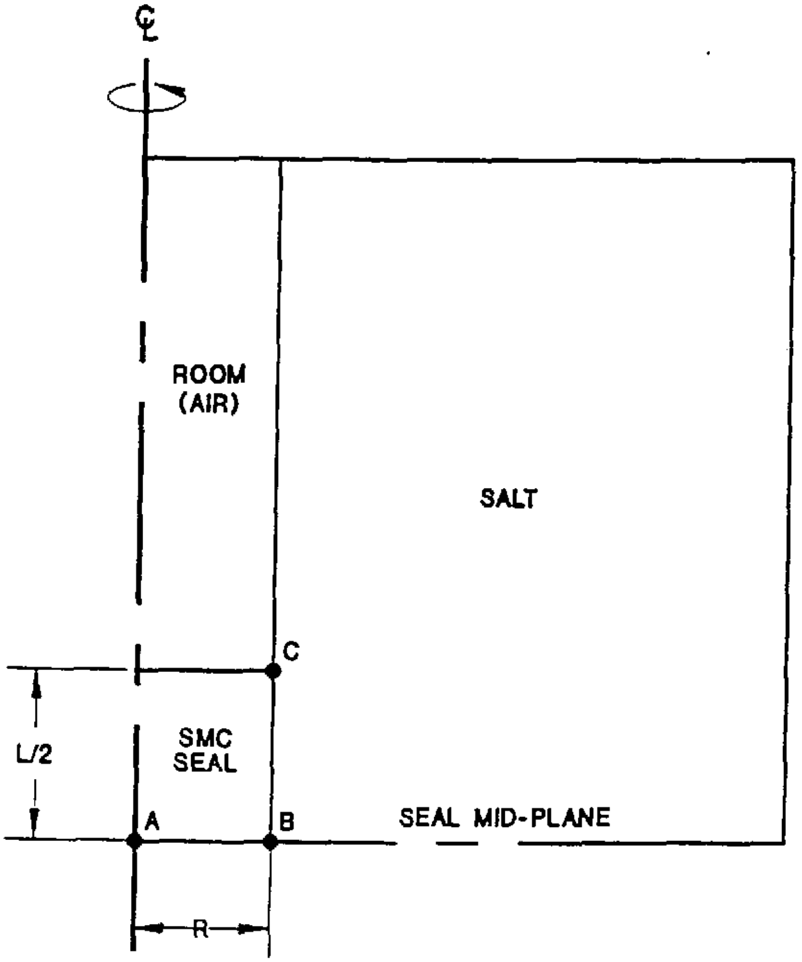
Checked by

Ref. Dwgs.

Date

RSI-213-94-006



POINT A = SMC CENTERLINE

POINT B = SMC/SALT INTERFACE AT SEAL MID-PLANE

POINT C = SMC/SALT INTERFACE AT SEAL END

L = SEAL LENGTH = (20 FT - CASE A; 6 FT - CASE B)

R = EQUIVALENT ROOM RADIUS = 2.66m

Figure 6-1. Axisymmetric Model.

4. Thermal creep of salt and sequentially updating the stiffness of concrete in a "smooth" fashion from zero at t = 1 yr to its intact stiffness at t = 1.02 yrs.
5. Thermal creep of salt using intact stiffness of concrete for an additional 49 yrs.

6.2 Cases Examined

In the baseline case (Case A), an emplacement length of 20 ft is examined. Case B considers an emplacement length of 6 ft.

7.0 RESULTS

Results include: (1) radial stresses along the SMC/salt interface, (2) location and magnitude of maximum shear stresses within the SMC, and (3) location and magnitude of tensile stresses within the SMC.

7.1 Radial Stresses

Radial (normal) stresses (σ_r) develop in the SMC as a result of restraining the creep of the surrounding salt in the opening. The magnitude and time of occurrence of these radial stresses within the SMC is of concern in light of the specified design strength of the concrete. In general, the spatial variation of the radial stresses along the SMC/salt interface is nearly uniform over the central ¾ length of the emplacement for all times. At the end of the emplacement, the stresses appear to become concentrated (singular?) because of the traction-free condition along the room periphery. Consequently, the maximum radial stresses will occur at the ends. The maximum radial stress that develops in the SMC decreases as the emplacement length increases [DeVries, 1993].

The time variation of the radial stresses in the SMC along the salt interface is shown in Figure 7-1 for a 20-ft-length emplacement (Case A). The maximum radial stress at the midplane (Point B, Figure 6-1) is approximately 20 MPa and occurs at about 10 yrs. Thereafter, the radial stresses decrease asymptotically toward their final steady-state values. The maximum radial stress at the end (Point C, Figure 6-1) is estimated to be greater than 45 MPa. The intermediate curves shown in Figure 7-1 represent results at the quarter points between B and C.

For the 6-ft-length emplacement (Case B), the maximum radial stress at the centerline is approximately 22 MPa and occurs at approximately 3 yrs (Figure 7-2). The maximum radial stress at the end exceeds 50 MPa. For Case B, only the results at the midplane and ends are shown.

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Date

RSI-213-94-007

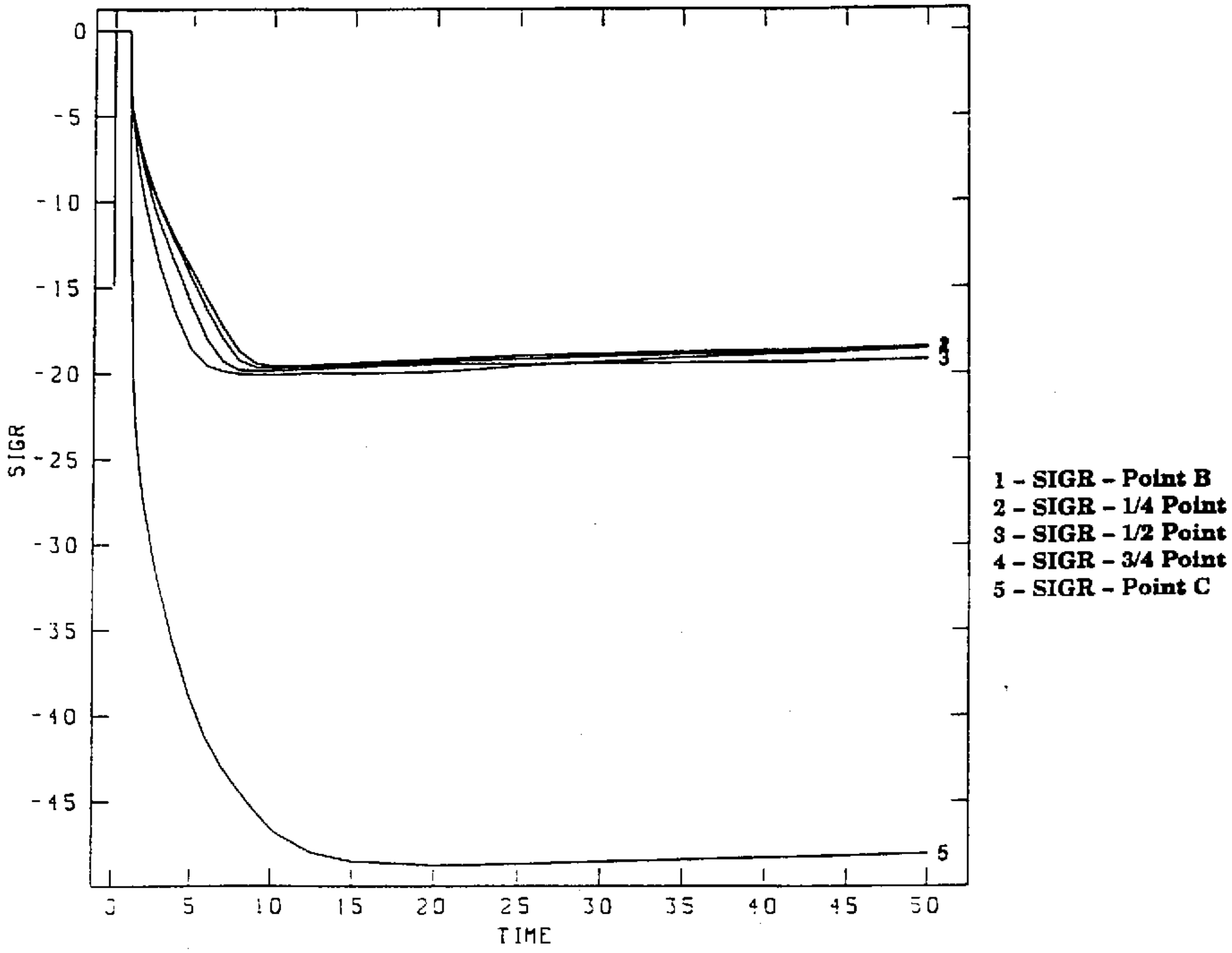

Figure 7-1. Radial Stresses — Case A.

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RSI-213-94-008

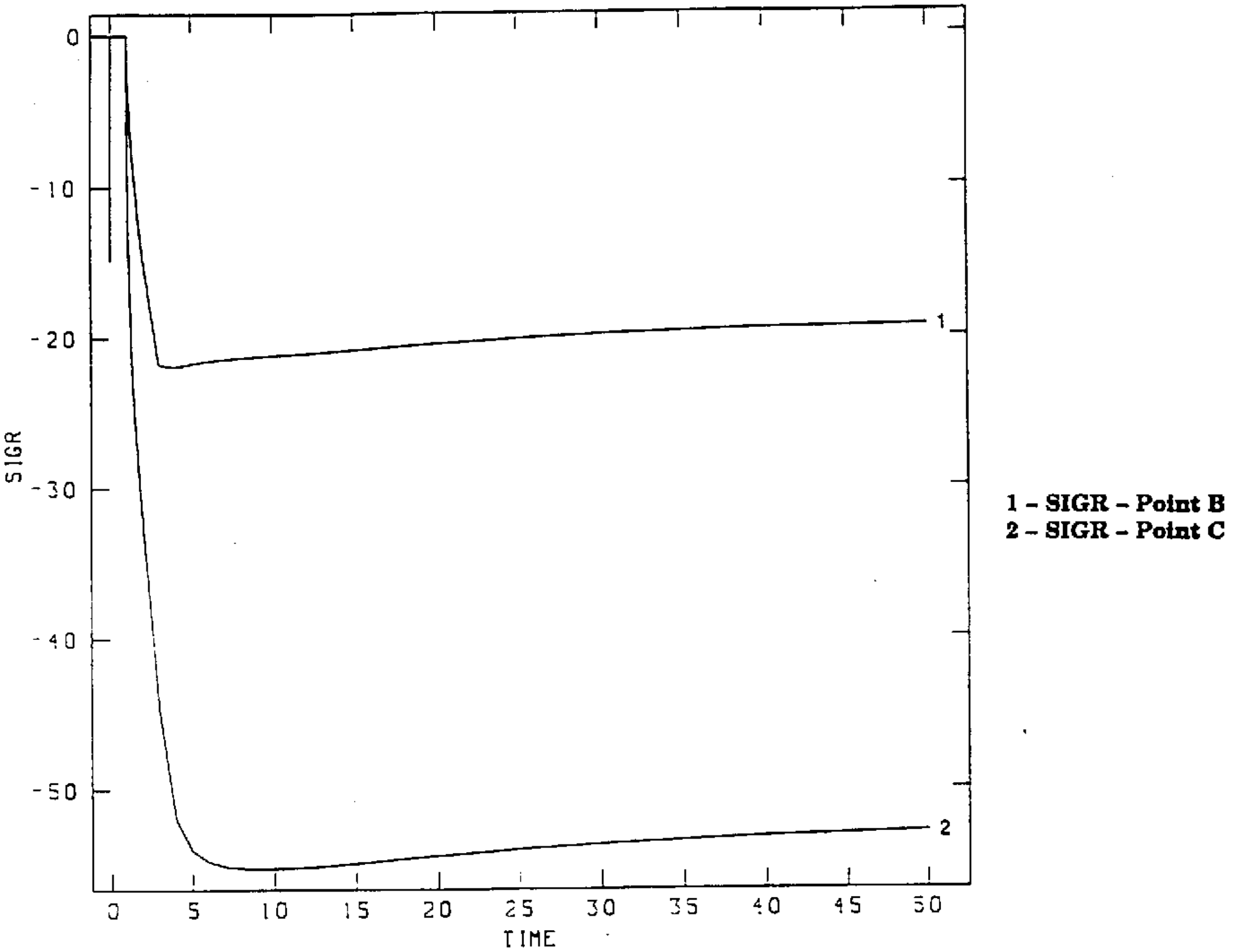

Figure 7-2. Radial Stresses — Case B.

7.2 Maximum Shear Stresses

The maximum shear stresses (τ_{max}) within the SMC are calculated from the maximum and minimum principal stresses (σ_1, σ_3) using the following equation:

$$\tau_{max} = 0.5 \, | \, \sigma_1 - \sigma_3 \, | \qquad (7\text{-}1)$$

The maximum shear stresses, in general, increase with time after emplacement of the SMC. As with the radial stresses, the shear stresses become singular (concentrated) at the end. The shear stresses increase as the length decreases. Depending on the strength criteria of the concrete, the development of high shear stresses increases the potential for failure (cracking) of the concrete.

The maximum shear stress at the centerline of a 20-ft-length emplacement (Case A) is approximately 11 MPa at 50 yrs (Figure 7-3). Near the ends, the maximum shear stress exceeds 43 MPa.

Near the center of a 6-ft-length emplacement (Case B), the maximum shear stress increases to approximately 15 MPa by 50 yrs (Figure 7-4). At the ends, the maximum shear stress may exceed 50 MPa.

7.3 Tensile Stresses

Development of tensile stresses within the SMC in the axial direction (σ_z) can occur because of the inward creep of the surrounding salt against the concrete, the bonding between the concrete and the salt, and the traction-free condition along the ends of the emplacement. These tensile stresses increase the likelihood of cracking of the concrete since unreinforced concrete is weak in tension. In general, the maximum principal stresses are the axial stresses within the SMC. Along the SMC/salt interface, the axial stress decreases (becomes compressive) during the first few years after emplacement (thermal expansion is dominant), then increases (becomes tensile) at later times (salt creep is dominant). These tensile stresses increase as the length is decreased.

The maximum principal stresses along the SMC/salt interface of a 20-ft-length emplacement are shown in Figure 7-5. At the center, σ_1 decreases to approximately –5 MPa (compression) at 5 yrs, then increases asymptotically to about 3 MPa (tension) at the end of the simulation time (50 yrs). The maximum tensile stresses increases toward the ends. These stresses are calculated to exceed 40 MPa at the ends, but this magnitude is unrealistic because localized yielding will have occurred to relieve the stress buildup and because the stress may be an artifice of numerical modeling.

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RSI-213-94-009

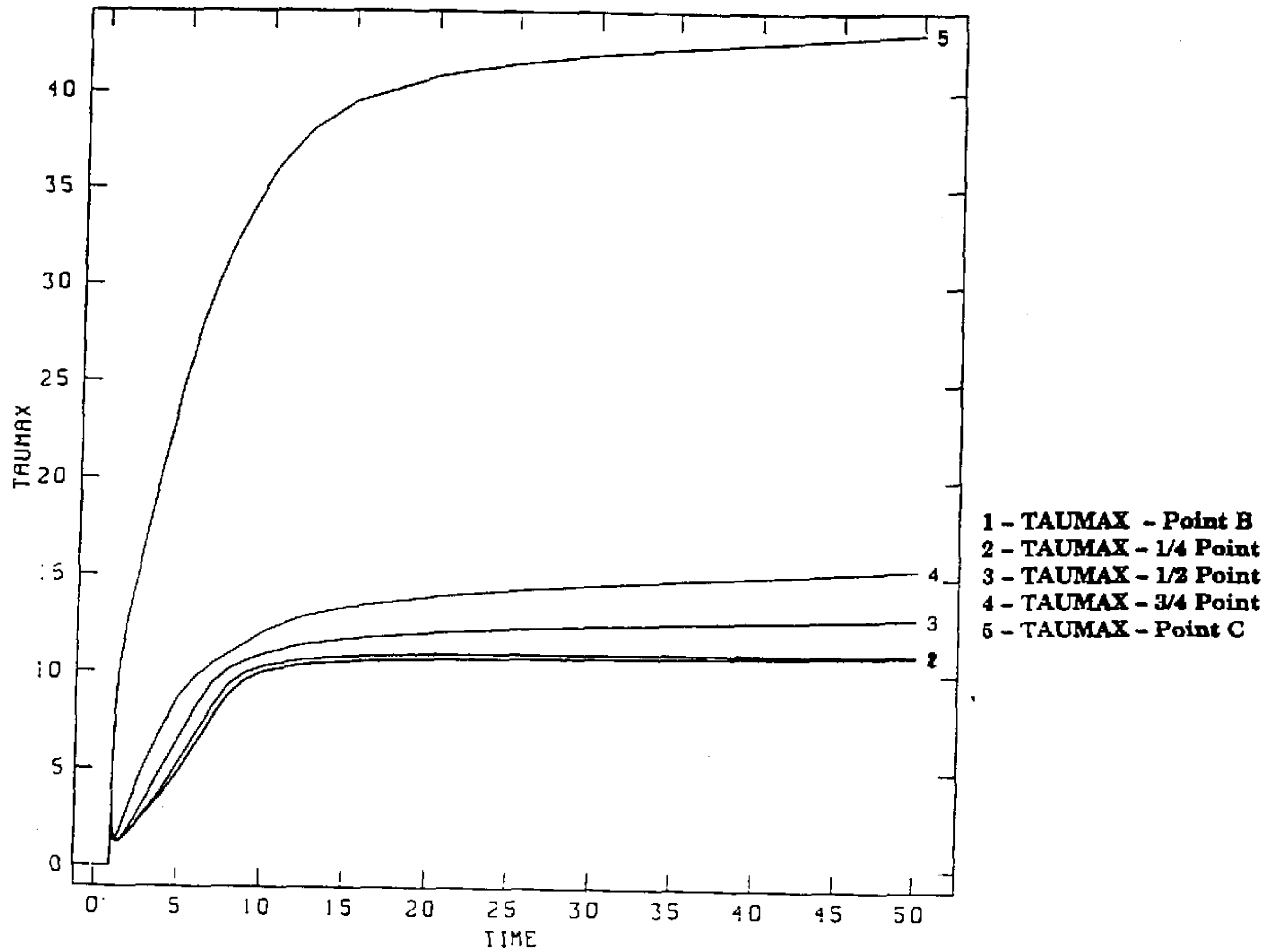

Figure 7-3. Maximum Shear Stresses — Case A.

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Date January 11, 1994

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Checked by

Ref. Dwgs.

Date

RSI-213-94-010

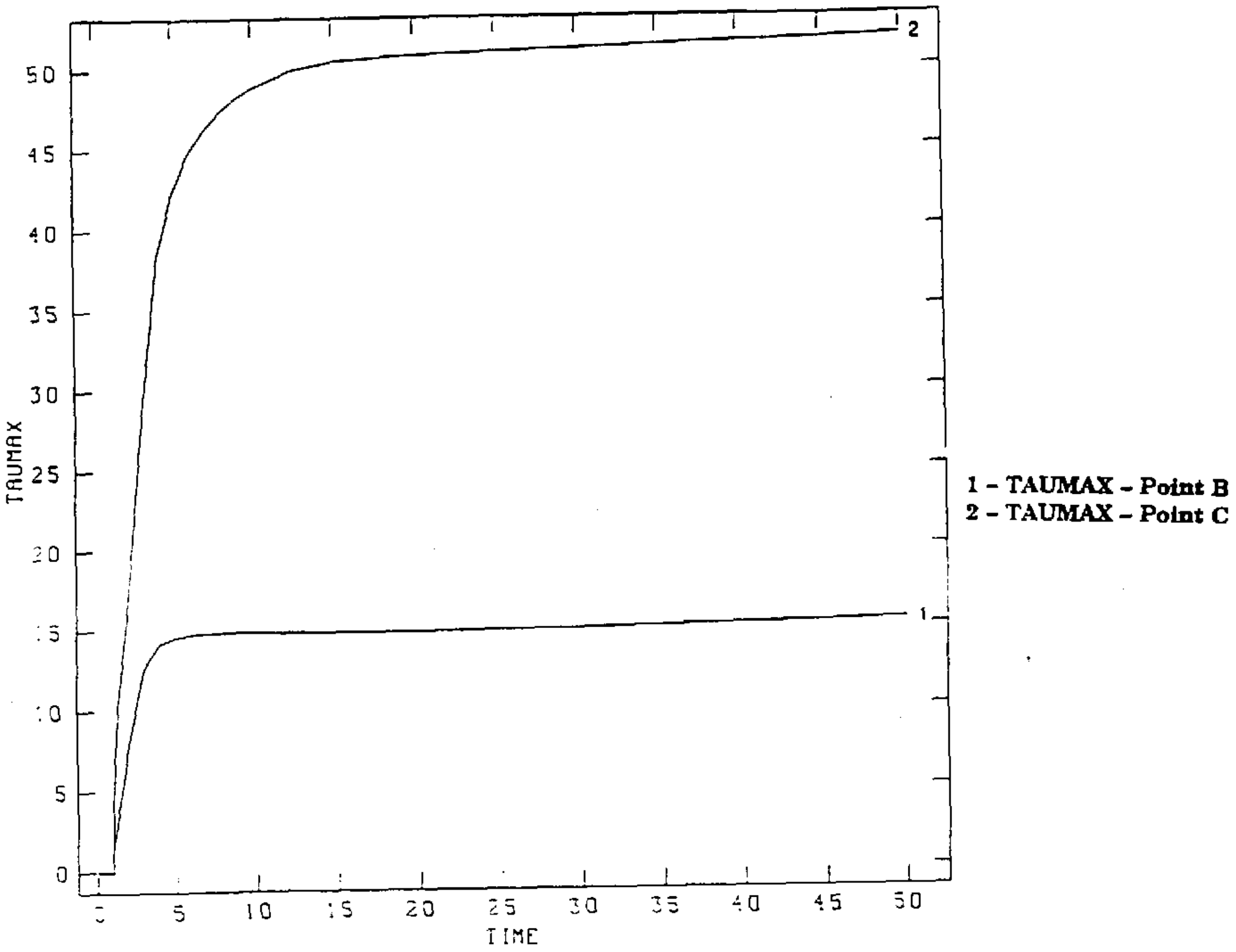

Figure 7-4. Maximum Shear Stresses — Case B.

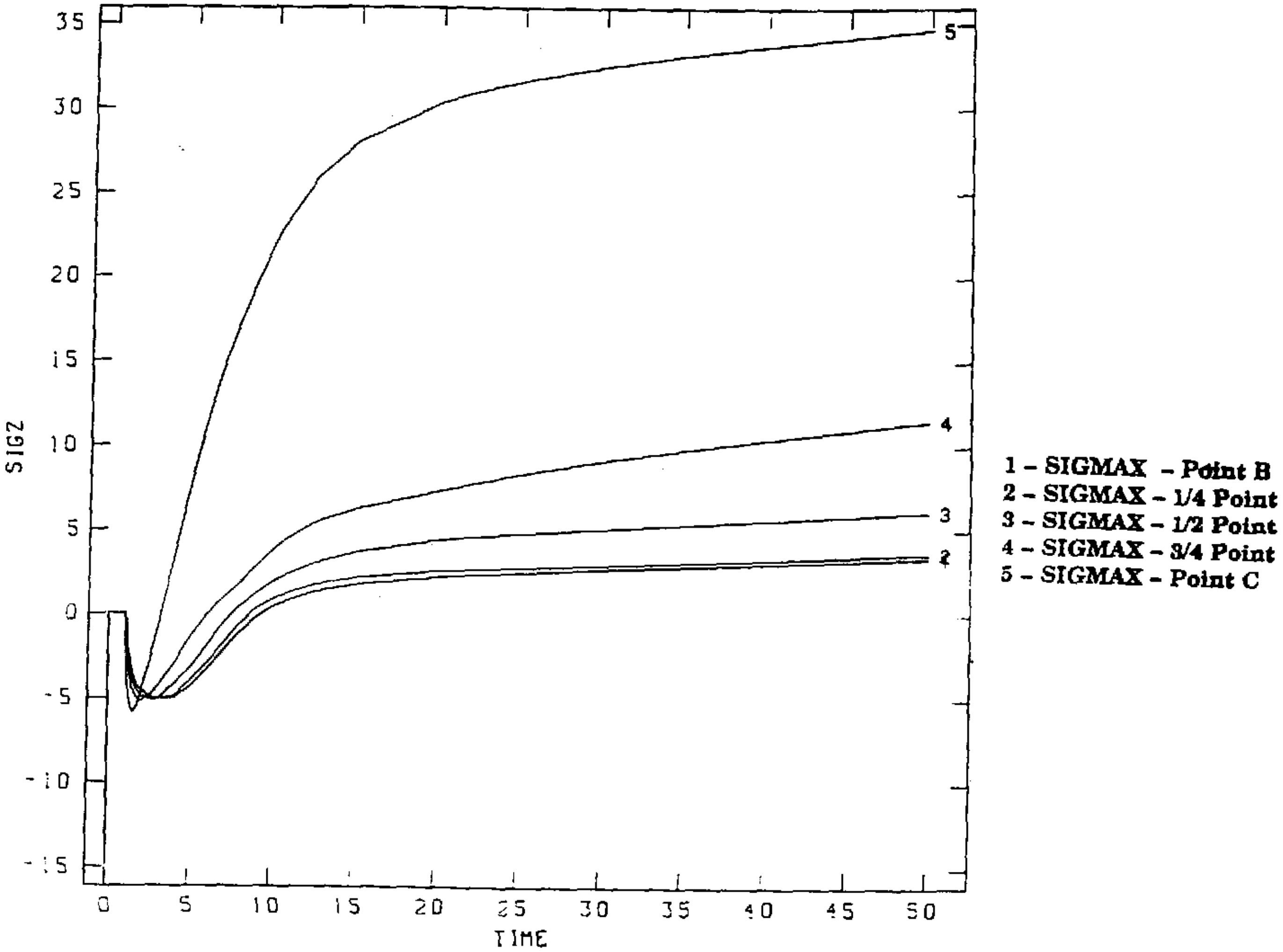

Figure 7-5. Maximum Principal Stresses — Case A.

The maximum principal stresses along a 6-ft-length emplacement are shown in Figure 7-6. At the center, σ_1 decreases to approximately –5 MPa at 5 yrs, then increases to nearly to 10 MPa by 50 yrs. The maximum principal stress near the ends is calculated to be 50 MPa by 50 yrs.

8.0 REFERENCES

Bailey, D. A., M. Grieves, and D. Mann, 1992. *Preliminary Design Criteria for the Waste Isolation Pilot Plant Sealing System Data Base Document*, prepared by Sandia National Laboratories, Albuquerque, NM, and Parsons Brinckerhoff Quade & Douglas, Inc., San Francisco, CA.

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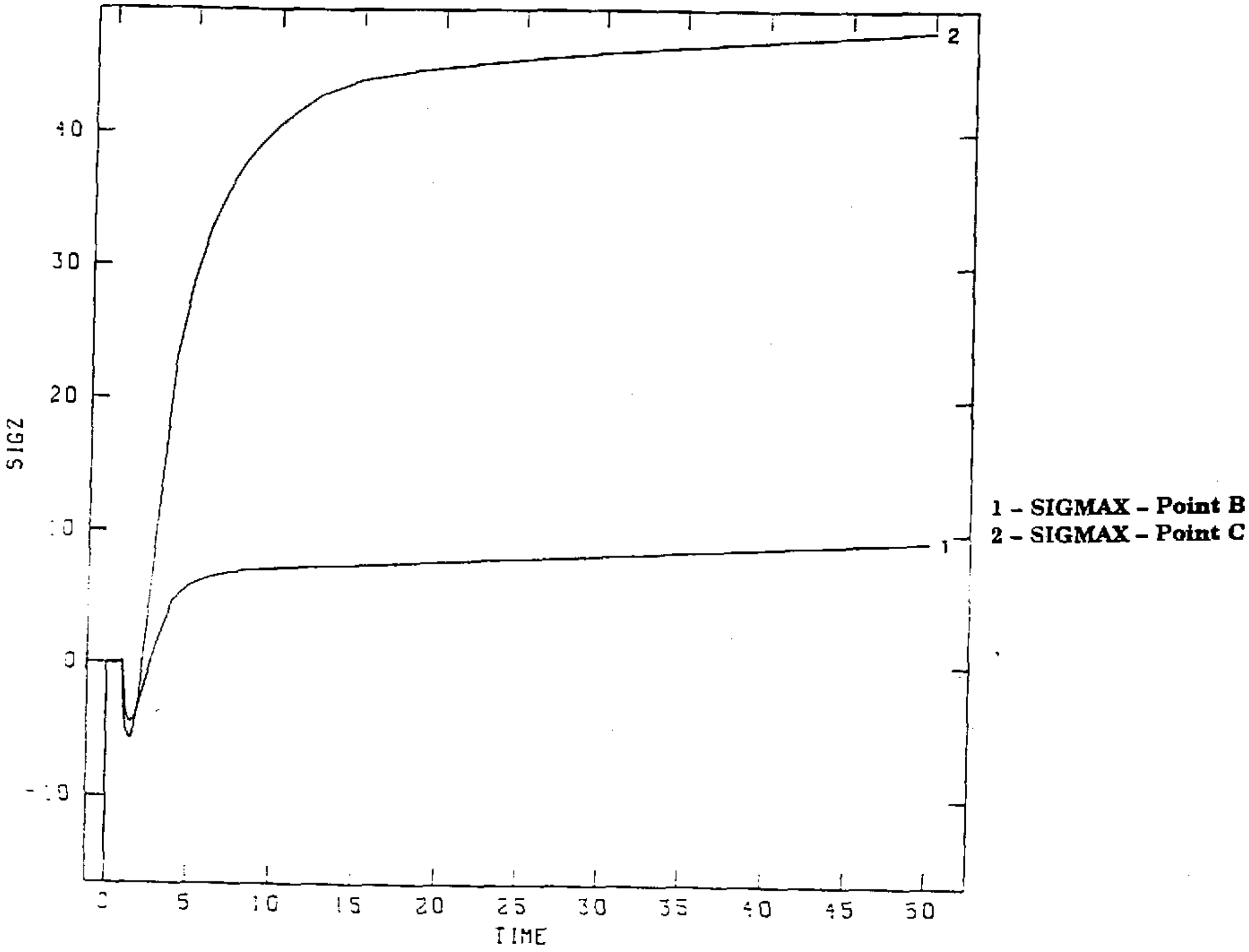

Figure 7-6. Maximum Principal Stresses — Case B.

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CONTRACT NUMBER 4060

PROJECT TITLE WIPP Conceptual Seal Design

CALCULATION DESCRIPTION SMC Thermal Calculations

DESIGN ENGINEER (SIGNATURE) 1-11-94 (DATE)

CHECKER (SIGNATURE) 2-10-94 (DATE)

PROJECT ENGINEER (SIGNATURE) (DATE)

QUALITY ASSURANCE (SIGNATURE) (DATE)

CALCULATION REVS		DATES		DATES		DATES		DATES
REVISION DESCRIPTION								
DESIGN ENGINEER								
CHECKER								
PROJECT ENGINEER								

STATUS	IN PROGRESS	CHECK	FOR APPROVAL	FINAL	VOID	HOLD	OTHER
	X	X	X				

REASON FOR VOID OR HOLD

INDEX

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Exhibit A

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Exhibit B

Design Verification Checklist

DESIGN VERIFICATION CHECKLIST

☒ CALCULATION
☐ DRAWING
☐ REPORT
☐ OTHER (Specify)
☐ SPECIFICATION

DOCUMENT NUMBER: 4060 A141-GE-07
TITLE: Rock Mechanics Analysis of SMC
REV. NO.: ——— PROJECT/TASK NO.: 4060/A141
ASSIGNED VERIFIER: L.L. Van Sambeek

List any related task documents which the assigned verifier must review in order to complete this verification:

VERIFICATION CRITERIA	YES	NO	N/A
1. Was the design input correctly selected?	X		
2. Are assumptions necessary to perform the design activity adequately described and reasonable?	X		
3. Where necessary, are the assumptions identified for subsequent reverifications when the detailed design activities are complete?	X		
4. Was an appropriate design method used?	X		
5. Was the design input correctly incorporated into the design?	X		
6. Is the design output reasonable compared to design input?	X		
7. Are the necessary design input and verification requirements for interfacing organizations specified in the design documents or in supporting procedures or instructions?			X
8. Are applicable regulatory and functional requirements considered in the design?			X
9. Have operational considerations been adequately addressed?			X
10. Can the design, as presented, be developed using reasonably available technology?			X
11. Have natural phenomena (seismic, flood, tornado) been considered in the design?			X
12. Are design documents accurate, consistent, sufficiently detailed, and of professional quality?	X		
13. Is each page of the document legible and reproducible?	X		
14. Have any required corrective actions been identified and documented? (circled changes)	X		

15. List all computer codes used. Have they been appropriately verified?

Computer Codes Listed in Table 6-1. Codes are internally verified.

16. Method of verification:
- [✓ Design review]
- Alternate calculation (location)

Verifier's Signature ______________________ Date: Feb 10 '94

4/91

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PROJECT TITLE WIPP Conceptual Seals Design
CALCULATION DESCRIPTION Rock Mechanics Analysis of SMC

DESIGN ENGINEER Marc C. (SIGNATURE) Jan 11, 1994 (DATE)
CHECKER (SIGNATURE) (DATE)
PROJECT ENGINEER (SIGNATURE) (DATE)
QUALITY ASSURANCE (SIGNATURE) (DATE)

CALCULATION REVS		DATES		DATES		DATES		DATES
REVISION DESCRIPTION								
DESIGN ENGINEER								
CHECKER								
PROJECT ENGINEER								

STATUS | IN PROGRESS | CHECK | FOR APPROVAL | FINAL | VOID | HOLD | OTHER

REASON FOR VOID OR HOLD

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Exhibit A
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