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PACER Program. FY 1974 LASL Activity. References

Compiled by

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PACER PROGRAM. FY 1974 LASL ACTIVITY.

REFERENCES

Compiled by

R. G. Shreffler

ABSTRACT

This report is a compilation of the previously unpublished, unclassified references cited in LA-5754-MS (October 1974), and each is identified by the number assigned to it in that publication.

Ref. 2. (p. 2) "PACER Program Phase I - Theoretical and Laboratory Studies," DOS-1-81. Initial Issue: April 2, 1974.

Ref. 3. (p. 86) "Project PACER Final Report" and "Project PACER Final Report - Appendixes," RDA-TR-4100-003, July 1974.

Ref. 4. (p. 413) "Fusion Power in Ten Years - Project PACER," RDA-JTR-4100-002 (Revised), July 1974.

Ref. 5. (p. 434) "Constraints on PACER Thermonuclear Explosives," DOS-1-74 (Revised), November 28, 1973.

Ref. 10. (p. 436) "PACER Opacity Calculation." Letter from F. R. Gilmore to D. Barfield, December 21, 1973.

Ref. 11. (p. 437) "PACER Opacity Calculations." Letter from D. Barfield to F. R. Gilmore, January 7, 1974.

Ref. 12. (p. 439) "PACER Phase 1 Report." Memo from W. D. Barfield to R. G. Shreffler, February 13, 1974.

Ref. 14. (p. 441) "RADFLO Calculations of PACER Cavity and Supporting Theoretical and Experimental PACER Effort." Memo from R. G. Shreffler to Distribution, January 14, 1974.

Ref. 15. (p. 444) "PACER: Experiments on Opacity of Water." Memo from Llewellyn H. Jones to R. G. Shreffler, February 26, 1974.

Ref. 16. (p. 447) "Comments on L. Jones' Memo." Memo from David Barfield to R. G. Shreffler, March 1, 1974.

Ref. 17. (p. 450) "PACER - Experiments on Opacity of Water-NaCl System." Memo from J. Zinn to R. G. Shreffler, March 1, 1974.

Ref. 18. (p. 451) "PACER - Expts. on Opacity of Working Fluid." Memo from Llewellyn H. Jones to R. G. Shreffler, March 6, 1974.

Ref. 19. (p. 453) "PACER Experiments." Memo from R. G. Shreffler to Llewellyn Jones, April 5, 1974.

Ref. 23. (p. 454) "Contribution to PACER Program Summary Document - Project 3 - Engineering." Memo from T. J. Merson to R. G. Shreffler, August 30, 1974.

Ref. 24. (p. 469) "Environmental Review - PACER." Memo from J. J. Koelling to R. G. Shreffler, February 7, 1974.

Ref. 27. (p. 476) "The Association of the PACER Program and the Nuclear Weapons Program," DOS-1-82, November 29, 1973.

Ref. 28. (p. 488) Letter from F. C. Gilbert to Harold M. Agnew, February 7, 1974.

Ref. 29. (p. 489) Letter from R. G. Shreffler to F. C. Gilbert, February 15, 1974.

Ref. 30. (p. 492) Letter from R. G. Shreffler to Lt. Gen. Warren D. Johnson, May 31, 1974.

Ref. 31. (p. 495) Letter from Lt. Gen. Warren D. Johnson to Robert Shreffler, June 27, 1974.

Ref. 32. (p. 497) "Appendix D, Statement of Work, Contract No. AT(29-2)-3324." Undated.

Ref. 33. (p. 500) "PACER Budget." Memo transmitting 189a from R. G. Shreffler to R. F. Taschek, February 13, 1974.

Ref. 34. (p. 501) Letter from R. G. Shreffler to Michael Daly, Senator Montoya's staff, February 26, 1974.

Ref. 35. (p. 502) Letter from Maj. Gen. Ernest Graves to Robert G. Shreffler, April 18, 1974.

Ref. 36. (p. 503) "PACER. Proposed Objectives and Budget for FY 75," DOS-1-107, April 25, 1974.

Ref. 37. (p. 509) Letter from H. M. Agnew to Maj. Gen. Ernest Graves, April 26, 1974.

Ref. 38. (p. 511) "PACER. Proposed Objectives and Budget for FY 75," DOS-1-111, May 7, 1974.

Ref. 39. (p. 530) "PACER Presentation for JCS Delegate to SALT and Members of the Verification Panel Working Group," DOS-1-118, August 1, 1974.

Ref. 40. (p. 542) Monthly reports by RDA and LASL for FY 74 dated August 15, 1973, September 10, 1973, October 12, 1973, November 21, 1973, December 14, 1973, January 14, 1974, March 25, 1974, April 24, 1974, May 17, 1974, and June 11, 1974.

[redacted]

Ref. 2

DOS-1-81

PACER PROGRAM

PHASE 1 - THEORETICAL AND LABORATORY STUDIES

PART I - PROGRAM DEFINITION

Introduction

This document outlines the initial phase of the PACER program. The objectives of this phase are:

- Theoretical investigation of all physics and chemistry problems
- Conceptual solution of all engineering design problems
- Fundamental materials creep and rupture and corrosion tests
- Engineering componetry testing as required
- Theoretical and laboratory studies of breeding and recovery
- Preliminary economic and system analysis of burner reactor utilization.
- Survey of all salt domes within the U.S.; development of criteria for salt dome selection; survey of methods for cavity construction.
- Investigation of the possibility of applying PACER technology to the development of a nuclear test and effects facility.

This planning document consists of a number of parts:

Part 1 - Divides the Phase 1 program into seven projects which in turn are subdivided into tasks.

Part 2 - Describes the experiments in support of Phase 1.

Part 3 - Defines the Phase 1 budget.

There are a number of purposes for this document:

- It will supply the necessary documentation needed to facilitate the management of a complicated and expensive program.
- It will serve as a principal communication and coordination instrument. There are at least four organizations directly responsible for the program: AEC Headquarters, ALO, LASL, and RDA.
- It will supply the necessary basis for determining budgets and schedules.

DOS-1-81

April 2, 1974

PACER PROGRAM
PHASE 1 - THEORETICAL AND LABORATORY STUDIES
PART I - PROGRAM DEFINITION

ALO Contract Officer: Harry Fish

AEC Program Manager: R. G. Shreffler (R. E. Roush, Alternate)

RDA Supervisor: H. Hubbard (E. Martinelli, Alternate)

DESCRIPTION:

The PACER Program is outlined in Reference 1. The goals for Phase 1 of the program are stated in the introduction to this document. The program consists of the following projects:

Project 1	Thermonuclear Device
Project 2	Cavity Phenomenology
Project 3	Engineering
Project 4	Economics
Project 5	Safety and Environmental Considerations
Project 6	Fuel Recovery and Processing
Project 7	Geology, Site Definition and Selection and Cavity Construction
Project 8	Nuclear Test and Effects Facility
Project 9	System Analysis, Coordination and Planning

RESOURCES:

A detailed breakdown of resources is included in Part III of this document. The funding for the current year is summarized as follows:

R&D Associates is funded for $247,000 under Contract AT(29-2)-3324 for FY 1974. Contractual obligations disperse the RDA funds in the following manner:

Manpower	$217K
Computer	14K
Travel	8K
Consultants	8K

LASL is funded at a level of $200,000. This money is distributed as follows:

DOS-1	Project Management	$ 34.1K
ENG	Engineering Design	37.4K
J	Fireball and Radiation Calculations & Site Selection	11.8K
T	Hydrodynamic and Opacity Calculations	51.1K
TD	Nuclear Explosive Design	5.7K
WX	Physical Chemistry & Cavity Structural Calculations	59.9K

MILESTONES:

4/74 Program Summary Report. On this date it is intended that summary reports from the nine projects will be completed and compiled into the Program Summary Report.

STATUS:

Detailed definition and funding for the entire program are under way. All projects are under way with specific emphasis on Projects 1, 2, and 3.

REFERENCES:

1. RDA Proposal 72-26, Electric Power Generation by Thermonuclear Explosions Contained in Salt Domes, October 1972. Secret.
2. DOS-1-54, Electric Power Generation by Thermonuclear Explosions Contained in Salt Domes, A Joint LASL-RDA Proposal, June 1973.
3. DOS-1, Electric Power Generation by Thermonuclear Explosions Contained in Salt Domes. Meeting July 6, 1973 at LASL.
4. DOS-1, July 17, 1973, Shreffler to Giller re FY 74 funding.
5. DOS-1-58, Electric Power Generation by Thermonuclear Explosions Contained in Salt Domes, July 1973 Progress Report.
6. DOS-1-62, August 1973 Progress Report.
7. DOS-1-71, September 1973 Progress Report.
8. DOS-1-77, October 1973 Progress Report.
9. DOS-1-76, PACER Program, Part I. General Discussion November 5, 1973.
10. DOS-1-82, The Association of PACER and the Nuclear Weapons Program, November 29, 1973.
11. DOS-1-85, November 1973 Progress Report.
12. DOS-1-88, December 1973 Progress Report.

PROJECT 1 : Thermonuclear Device*

PROJECT LEADER: LASL, R. E. Roush

DESCRIPTION :

The development of an appropriate thermonuclear device is essential to the success of the program. A list of constraints upon this device is listed in reference 1. Such constraints as device security and safety, the use of natural resources, the influence of breeding and cost, and the appropriate yield range are considered. Characteristics, which are deduced in reference 1 from the constraints are the following:

1. Yield: 100 kt maximum.
2. Thermonuclear fuel: deuterium
3. Minimized: tritium, lithium, plutonium, fission products, induced activity.
4. No restriction within reason on size and weight
5. Highest priority placed on security and safety
6. Minimum cost consistent with constraints

The project is divided into three tasks for Phase 1:

Task 1.1: Device Design: To develop device design drawings meeting the above characteristics, and devices for scale experiments to be executed in Phase 2. No hardware will be procured. Device output will be computed.

Task 1.2: Device Cost: To define the basis for cost and pricing estimates, and to determine best estimates for the individual devices.

Task 1.3: Device Safety and Security: To outline methods which insure safe and secure handling of nuclear explosives from production plants to detonation, and to insure these methods apply to the designs.

RESOURCES:

Resources are spelled out with each task.

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*The "device" is defined to include the entire capsule which is released to explode within the cavity. It contains the nuclear components, fusing and firing, safeing systems, and cases for breeding, radiation suppression, insulation and structure.

Project 1

MILESTONES:

2/74	Preliminary sketches of device designs completed.
2/74	Preliminary cost procedures established.
3/74	Preliminary device safety and security procedures defined.
5/74	Draft of document, "PACER Thermonuclear Explosive" prepared.
5/74	Cost estimate of first device determined.
-	Device designs completed
	Cost procedures established
	Safety and security procedures established

STATUS:

Reference 1 has been written.

Designs for 10 and 100 kt yield devices are being explored with TD Division. Meeting with ALO in mid-January initiated device cost analyses.

REFERENCE:

1. DOS-1-74, Revised, November 28, 1973: PACER Thermonuclear Explosive Constraints.
2. DOS-1-98, "Criteria for Developing, Production, and Handling of PACER Device," (in progress).

TASK 1.1 : Device Design

PROJECT LEADER: LASL, R. E. Roush

DESCRIPTION :

The goal of this task is the design of appropriate PACER devices, keeping in mind the constraints and characteristics outlined in Reference 1. Two devices with yields of 10 and 100 kt will be developed with the prototype in mind. Two other devices will be designed for the scale experiments; one will be high explosive, the other will be nuclear with a yield in the neighborhood of 100 tons. All four devices, to the degree expedient, will have the same external configuration, weight and center of gravity. To the degree possible, all will operate with the same fuzing and firing, safety, and security devices and procedures. As a specific part of this task, calculations will be made exposing the amount of device debris: inert components, tritium, plutonium, uranium, fission products, and induced activity. A calculation will be made of the radiation level in the working fluid.

MILESTONES:

2/74 Preliminary sketches of device designs completed.

RESOURCES:

DOS-1	Supervision
ENG-6	Preliminary engineering drawings
TD	Theoretical design
WX	Engineering design and drafting
RDA	Consultation

STATUS:

Designs are under way.

REFERENCE:

1. DOS-1-74, Revised, November 28, 1973: PACER Thermonuclear Explosives Constraints.

TASK 1.2 : Device Cost and Price

PROJECT LEADER: LASL, R. E. Roush

DESCRIPTION :

At the present time the incremental cost of peaceful nuclear explosives is based on their production being integrated with weapons production. In most cases this places a penalty on the peaceful nuclear explosives cost. Likewise, the present AEC pricing is based on a 1964 DPNE pricing policy statement. This pricing is based on the incremental cost plus added factors which again are derived from weapons cost experience.

The extremely large production rate requirements of explosive units for PACER will almost certainly necessitate a reevaluation of the capacity of the AEC integrated contractor production facilities. This reevaluation could lead to the conclusion that new and separate (from weapon) facilities will be required for the production of PACER nuclear explosives. Based on this premise, a new approach for determining the incremental cost and price of the PACER nuclear explosive will be required. This task will be to establish the procedures and to obtain the cost and price of PACER nuclear explosives. All effort will be carried out through ALO. Procurement of the devices is to take place within the AEC system with the understanding that prices will be competitive with commercial prices.

RESOURCES:

DOS-1	Coordination
ALO	Establish costing and pricing procedures, and determine cost from integrated contractors.

MILESTONES:

5/74	Preliminary cost procedures established and cost estimate of first device determined. Price procedures established.

STATUS:

Preliminary talks with ALO setting mid-January as time to start AEC cost study.

REFERENCE:

1. DOS-1-74, Revised November 28, 1973: PACER Thermonuclear Explosives Constraints.
2. UCRL-51386, August 1, 1973, The Report of the AEC Task Group on Special Materials for Plowshare, W. J. Hogan (secret).
3. UCRL-50410, March 8, 1968, Costs of Nuclear Explosives for Natural Resources Applications, R. E. Rawson, et al.
4. DOS-1-98, Criteria for the Development, Production and Handling of PACER Thermonuclear Devices. (In progress.)

TASK 1.3 : Device Safety and Security

PROJECT LEADER : LASL, R. E. Roush

DESCRIPTION :

Methods which insure safe and secure handling of nuclear explosives from production plants to detonation must be defined. These procedures will be used to evaluate the proposed device designs.

RESOURCES :

DOS-1	Coordination
WX-1	Consultation and design
WX-3	Consultation and design
Sandia	Consultation and design
ALO	Consultation

MILESTONES:

Preliminary device safety and security procedures defined.
Safety and security procedures established.

STATUS:

General ground rules set forth in Reference 1.

REFERENCES:

DOS-1-74, Revised, November 28, 1973: PACER Thermonuclear Explosive Constraints.

PROJECT 2 : Cavity Phenomenology

PROJECT LEADER: RDA, Hubbard/LASL, Shreffler

DESCRIPTION :

The complete history of the behavior of the cavity must be described from the time the mining of the cavity begins until the site is abandoned. Codes must be developed and laboratory experiments executed to completely expose the phenomena associated with the cavity. The tasks composing this Project are:

Task 2.1	Working Fluid: Choice based upon its interaction with the cavity walls, corrosion of the primary loop and device injection hardware, cost, safety implications, energy transfer properties.
Task 2.2	Nuclear Explosion Investigations ($t < 1$ sec): The interaction of the nuclear device explosion with the working fluid and the cavity wall at times until the behavior ceases to be one dimensional.
Task 2.3	Circulation of Working Fluid ($t > 1$ sec): A calculation of the circulation of the working fluid within the cavity to define the history of the fireball, and to demonstrate the behavior of heat transfer between the cavity and the primary loop.
Task 2.4	Cavity Integrity - Creep Effects: Assess the integrity of the cavity under overburden stresses, accounting for defects in the wall, anhydrite inclusions in the surrounding salt, the influence of time, and the state of the working fluid.

The feasibility of the program rests largely on the results of the investigations of the tasks and associated experiments composing this project.

RESOURCES:

Resources are spelled out with each task.

MILESTONES:

3/74	Project Summary Report (DRAFT) (Principal task milestones will be added here when resolved.)

STATUS:

Work is proceeding on all tasks.

REFERENCES:

See tasks.

TASK 2.1 : Working Fluid

PROJECT LEADER: LASL, Nutt/RDA, Hubbard

DESCRIPTION :

The choice and evaluation of an acceptable working fluid is crucial to the success of the program. Water was chosen initially as the candidate most likely to succeed. Subsequent efforts have confirmed this choice to be a good one, indeed it may be uniquely qualified, particularly if supplemented with the addition of nitrogen (air). However other possible backup fluids continue to be investigated.

RESOURCES:

DOS-1	Coordination
WX-2	Research and calculations

RDA
R. Lindgren, F. Gilmore, G. Kennedy (Consultant)

MILESTONES:

10/73	Preliminary choice of cavity working fluid (water)
3/74	Project Summary Report (Draft).

STATUS:

Numerous meetings have been held on this subject. Although Tasks 2.2 and the experiments (Reference 3) must be executed to finally define and confirm the choice, water with a few percent air is an almost certain selection. The summary report will expose all the subject.

REFERENCES:

1. S. Sourirajan and G. C. Kennedy, American Journal of Science, 260, p. 115, 1973, "The System H_2O-NaCl at Elevated Temperature and Pressures."
2. H. W. Hubbard, PACER Working Fluid and New Operating Conditions, September 25, 1973.
3. See Part II of this document. Experiments 1, 3, 7.
4. *DOS-1-92*, "Some *Cavity Stability Implications* on the *Use* of *Water* as the Working Fluid for PACER Power Generation," A. W. Nutt, February 25, 1974.

TASK 2.2 : Nuclear Explosion Investigation (t < 1 sec)

PROJECT LEADER : RDA, Hubbard/LASL, Shreffler

DESCRIPTION :

The explosion of the nuclear device and the subsequent behavior of the working fluid within the cavity at times until its behavior ceases to be one dimensional (< 1 sec). The calculation should give a number of data:

1. The shock and radiation interaction with the cavity wall.
2. The determination of the condition following the explosion; the state of the fireball is of particular importance. This serves as input to task 2.3.
3. The input to the seismic problem as it affects both the engineering and ecological aspects of the program.

RESOURCES:

DOS-1	Coordination
J-10	Consultation and computation of RADFLO
T-3	Consultation on hydrodynamics and coordination
T-4	Consultation on and computation of opacities

RDA

R. McLean, F. Gilmore, H. Hubbard, E. Martinelli

MILESTONES:

3/74	RADFLO calculations with water plus air
3/74	Project Summary Report (Draft).

STATUS:

J-10 has done a RADFLO calculation using dry air. They will do further calculations on air plus traces of water, water, and water plus traces of air. The latter calculations are dependent on opacity data being accumulated and developed by T-4. The air calculation indicated essentially no radiation to reach the cavity wall. The intention is to develop a working fluid of water with possible limited amounts of air to meet this same desirable criteria of no radiation on the wall. Reference 3 describes this activity. LASL progress to date has been good and is defined in Reference 5.

RDA has programs under way exploring most of the points outlined in the description.

REFERENCES:

1. J-10 Computer Records.
2. Penner and Varanasi, JQSRT 58, 391 (1965).
3. Memo, Shreffler to Distribution, "Radflo Calculations of Pacer Cavity and Supporting Theoretical and Experimental Pacer Effort," January 14, 1974, DOS-1-90.
4. See Part II of this document. Experiments 6, 7, 8.
5. Memo, Barfield to Shreffler, "PACER Phase 1 Report," February 13, 1974.

TASK 2.3: Circulation of Working Fluid (t > 1 sec)

PROJECT LEADER: LASL, Francis Harlow, Linda Simpson

DESCRIPTION :

To remove from the cavity all of the heat energy deposited by each explosion, it is essential to maintain adequate circulation of the working fluid. Molecular heat conduction alone is far from sufficient. Convective transport to the vicinity of the heat exchangers must occur. It may also be necessary to induce turbulence to enhance the heat transport.

At least three driving mechanisms can be visualized for the initiation and maintenance of mean-flow circulation:

1. The nonuniform deposition of heat from each explosion will result in buoyancy, which drives free convection. Assuming that the central region is hottest, the resulting "bubble" will rise along the axis, producing clockwise (negative) circulation in the r-z plane. The scale of circulation is likely to be the scale of the entire cavity.

2. Removal of heat will produce local cool regions with negative buoyancy, which will tend to fall. The induced circulation will likely be on the scale of the heat exchanger size, despite the fact that the cooled fluid may fall to the bottom of the cavity. Heat withdrawal at the top of the cavity will tend to induce counterclockwise (positive) circulation in the r-z plane, in competition with the explosion-driven circulation, whereas withdrawal at the sides may enhance the circulation. .

3. The withdrawal of the working fluid into the heat exchangers and subsequent return back to the cavity will tend to induce forced convection, and may also enhance the turbulence level in the cavity.

Qualitative estimates show that the intensity and duration of the various circulation patterns depend strongly on the level of turbulence. Because of this sensitivity, accurate calculations of the circulation patterns are crucial. Such accuracy will require computer solutions of the full fluid flow and heat transport equations. For this purpose, we are developing a general computer code for the study of the working fluid dynamics, through all stages of each explosion cycle. Full account is taken of the time-varying motions in the two-dimensional (axially-symmetric) configuration. The effects of buoyancy, turbulence and convection can then be studied efficiently and realistically for a full scope of parameter variations, with results that are expected to influence nearly all aspects of engineering and design.

RESOURCES:

DOS-1	Coordination
T-3	Consultation and Calculations
J-10	Calculations. Reference 1

RDA
Consultation

MILESTONES:

3/74	Project Summary Report

STATUS

A preliminary calculation has been made of the rising of the fireball from the center to the roof of the cavity by J-10. See Reference 1.

T-3 has developed the CIRCO code and checked it with preliminary calculations. Problems are now being run with an incompressible fluid to evaluate the circulation resulting from the influx and exit of working fluid from the primary loop. In addition the circulation resulting from the removal of heat from the cavity is being studied. Calculation of fireball behavior will follow.

REFERENCES

1. LA-5427-MS, PACER Program, A Strong Explosion in a Spherical Cavity; Two-dimensional Evolution, by E. Jones.

TASK 2.4 : Cavity Integrity - Creep Effects

PROJECT LEADER: RDA, Hubbard/LASL, Anderson

DESCRIPTION :

The objective of this task is to assess the integrity of the cavity under the overburden stresses, accounting for the effects of defects in the wall and anhydrite inclusions in the surrounding halite. Two dimensional calculations with existing codes will be made to determine the likelihood of excessive creep deformation or creep rupture of the cavity wall. The following analytical models will be considered:

1. Spherical cavity - pure halite: This baseline model will involve a perfect spherical cavity under static internal pressure and gravitational body forces in the surrounding material. This material will be taken as pure isotropic halite with axisymmetric temperature distribution and under steady state, temperature dependent creep. Variations will be made in parameters such as cavity size and depth, internal pressure, temperature distribution and creep characteristics to determine their effect on the creep deformation and creep rupture time for the halite.

2. Spherical cavity - halite/anhydrite medium: In this variation of the baseline model an attempt will be made to account for the effects of anhydrite inclusions in the halite. The model and approach will be similar to the baseline analysis except that the material will be modeled as a cylindrically orthotropic mixture of anhydrite and halite.

3. Cavity defects - pure halite: In this model, a family of cavity wall irregularities will be defined and the local stresses analyzed in order to study the influence of wall defect size and shape on creep rupture. Both axisymmetric and plane defects in the pure baseline halite will be considered.

RESOURCES:

DOS-1	Coordination
WX-3	Calculations
RDA	H. Hubbard, A. Field

MILESTONES:

11/73	TSSAS Operating
3/74	Project Summary Report

STATUS:

The TSSAS code has been slightly modified to meet PACER requirements. The calculations for Model 1 are being carried out at WX-3. Several runs have been completed. Experiments are being defined.

REFERENCES:

1. DOS-1-75, Determination of Cavity Stability in Long Term Creep, November 1, 1973.
2. See Part II of this document. Experiments 2, 8, 9.
3. WX-3 Trip Report - PACER Cavity Stability, C. A. Anderson, December 20, 1973.

PROJECT 3 : Engineering

PROJECT LEADER: RDA, L. Gore/LASL,T. Merson

DESCRIPTION:

This project includes all aspects of the engineering of the proposed power generation concept from the cavity/piping interface to and including the generating turbine. The explosive device injection system is also included. Pertinent to the engineering project will be the study of problems associated with the startup and emergency and final shutdown operations. Inherent in the study and solution of these problems will be the interaction with other project considerations in such areas as choice of working fluid, cavity wall stability and environment, safety and economics. Considerable interaction with laboratory experiments is required, especially those specifically designed to provide engineering design information. The engineering goal for Phase 1 is to complete all engineering concepts, criteria, calculations, and associated design drawings for scale experiments (Phase 2) and for the prototype development (Phase 3) of the primary loop and device injection. To accomplish this, the engineering project is subdivided into five tasks.

Task 3.1: Trade studies and engineering project coordination: To integrate inputs from many sources and study competing engineering concepts. Eventually to supply criteria and drawings for AE input to Phases 2 and 3.

Task 3.2: Primary loop: To resolve mechanical problems associated with the primary loop including pumps, heat exchangers, piping, valves, etc.

Task 3.3: Materials: To transform information from experiments and calculations into engineering recommendations for material choices. Specifically to consider corrosion, cost, and fabrication.

Task 3.4: Containment: To determine the sealing of access piping to the cavity wall and associated problems, and to design candidate seals for testing.

Task 3.5: Device injection: To study the problems and possible solutions associated with injecting the devices into the cavity.

RESOURCES:

Resources spelled out with each task. For the present responsibility at RDA rests with L. Gore, at LASL with T. Merson. They are supported by the engineering staffs of both organizations.

MILESTONES:

3/74 Prepare input to Program Summary Document.
Complete requirements for Phase 1.

STATUS:

Preliminary scoping calculations have been performed. Discussions among various engineers have been held to outline potential problems and solutions.

REFERENCES:

See tasks.

TASK 3.1 : Trade Studies and Engineering Project Coordination

PROJECT LEADER: RDA, L. Gore/LASL, T. Merson

DESCRIPTION :

Trade studies will be conducted to optimize choices for components of the engineering system. The purpose is to avoid incompatibilities and excessive costs, and to aid coordination and management. The objective is to supply criteria and drawings for A.E. input to Phases 2 and 3.

RESOURCES:

DOS-1	Coordination
ENG-6	Consultation
RDA	Consultation

MILESTONES:

3/74 Preparation of Program Summary Document for Project 3, Engineering, and for Experiments 3, 4, 5, 6, and 8.

STATUS:

REFERENCES:

1. RDA-IR-4100-001, "Throttled Steam for Power Generation," August 1973, by L. Gore.
2. RDA-IR-4100-002, "Gas Turbine Type Cycle for Power Generation," August 1973, by L. Gore.
3. RDA-IR-4100-003, "Pipe Sizes and Pumping Power," August 1973, by L. Gore.
4. RDA-IR-4100-007, "Pressurized Water Heat Exchangers," October 1973, by L. Gore.
5. RDA-IR-4100-015, "PACER Thermal Efficiency," December 1973, by L. Gore.

TASK 3.2 : Primary Loop

PROJECT LEADER: RDA,L. Gore/LASL, T. Merson

DESCRIPTION :

The objective of this task is to design the primary loop including such subsystems as piping, heat exchangers, pumps, valves, etc. It is the function of this task to provide sufficient design information that an AE can proceed with Phase 2 and 3 design. It is expected that this task will interface closely with the experimental program and even provide design input to several experiments.

RESOURCES:

DOS-1	Coordination
ENG-6	Engineering
RDA	Engineering

MILESTONES:

3/74 Contribution to Task 3.1 in preparation of Program Summary Document.

STATUS:

The references have been written.

REFERENCES:

1. RDA-IR-4100-006, "Preliminary Estimate of Size, Weight and Cost of Primary Loop High Pressure Pipes," October 1973, by L. Gore.
2. RDA-IR-4100-007, "Pressurized Water Heat Exchangers," October 1973, by L. Gore.
3. RDA-IR-4100-008, "All Steam Heat Exchangers," October 1973, by L. Gore.
4. See Part II of this document, Experiments 1, 3, 4, 6.
5. PACER Power Cycle Diagram, February 7, 1974.

TASK 3.3: : Materials

PROJECT LEADER: RDA, L. Gore/LASL,T. Merson

DESCRIPTION:

The objective of this task is to liaison with the materials testing experiments to provide support in the experimental apparatus design and to be certain that materials of engineering significance are evaluated in a meaningful manner. This task will be responsible for recommendations regarding choices of engineering materials including such data as corrosion, fabrication and cost.

RESOURCES:

DOS-1	Coordination
ENG-6	Consultation
RDA	Consultation

MILESTONES:

3/74 Contribution to Task 3.1 in preparation of Program Summary Document.

STATUS:

REFERENCES:

1. See Part II of this document, Experiments 1, 3, 5,6.
2. Preliminary Engineering Criteria for PACER Materials (in progress).

TASK 3.4 : Containment

PROJECT LEADER: RDA, L. Gore/LASL, T. Merson

DESCRIPTION :

The objective of this task is to study the problems of containment of the high pressure steam and to design the required seals around access piping. It will be the function of this task to provide input for the laboratory tests of candidate seal systems and aid in the design of experimental apparatus and to analyze experimental results. Interaction with the primary loop and device injection design efforts is required.

RESOURCES:

DOS-1	Coordination
ENG-6	Engineering
J-9	Consultation
RDA	Engineering

MILESTONES:

3/74	Contribution to Task 3.1 in preparation of Program Summary document.

STATUS:

REFERENCES:

1. See Part II of this document, Experiments 3, 4, 5, 6, 8.
2. Preliminary Engineering Criteria for PACER Containment (in progress).

TASK 3.5 : Device Injection

PROJECT LEADER: RDA, L. Gore/LASL,T. Merson

DESCRIPTION:

The objective of this task is to design a system for injecting the devices into the cavity. This will require integration of information and design criteria from other tasks and projects. The objective is to supply criteria and drawings for AE input to Phases 2 and 3.

RESOURCES:

DOS-1	Coordination
ENG-6	Engineering
J-6	Consultation

MILESTONES:

3/74	Contribution to Task 3.1 in preparation of Program Summary document.

STATUS:

References have been prepared. Discussions have been held.

REFERENCES:

1. ENG-6-132, "Preliminary Thoughts on Device Injection for PACER," December 1973, by T. Merson.
2. See Part II of this document, Experiments 1, 4, 5, 6.
3. Preliminary Engineering Criteria for Device Injection Design (in progress).

PROJECT 4 : Economics

PROJECT LEADER: RDA, Hubbard/LASL, Shreffler

DESCRIPTION :

This proposal for electrical energy generation must be competitive with others available in the same time period; in particular with conventional and nuclear reactor power stations. Estimates will be made of the contribution to the cost of electricity from the fuel, cavity, and generating equipment for the various options under consideration. This amounts to updating the analysis contained in the RDA proposal with the benefit of better cost figures.

A second approach to the economics is the consideration of self-contained energy parks which include fuel fabrication and assembly, recovery, and power generation. In this concept nuclear devices are never shipped outside the facility and the plutonium or ^{233}U required (and much more if desired) is produced and recovered and fabricated within the park. This promising concept will be analyzed using best current estimates of costs.

RESOURCES:

DOS-1	Coordination and Compilation
RDA	Coordination and Compilation

MILESTONES:

3/74 Project Summary Document

STATUS:

Reference:

1. RDA Proposal 72-26, Electric Power Generation by Thermonuclear Explosives Contained in Salt Domes, October 1972, SECRET, pp. 38-42.

PROJECT 5 : Safety and Environmental Considerations

PROJECT LEADER: RDA, Hubbard/LASL, Shreffler

DESCRIPTION :

Safety and environmental considerations have overriding priority in the development of all projects of the program. The project consists of the following tasks:

Task 5.1	To examine each aspect of the concept and design for the safety implications.
Task 5.2	To better estimate both the seismic effects of the nuclear explosion upon all the mechanical components of the system, and the effects at the surface of the ground.
Task 5.3	To investigate the legal implications of the program from a safety point of view
Task 5.4	To make recommendations as to how and when the project should be presented to the public. (During the first year, or until an accepted policy has been established, the project should be treated with discretion.)

RESOURCES:

Resources are spelled out with each task.

MILESTONES:

3/74	Draft of document satisfying Task 5.4
3/74	Project Summary complete

STATUS:

Work on Task 5.4 is under way.

REFERENCE:

1. RDA Proposal 72-26, Electric Power Generation by Thermonuclear Explosives Contained in Salt Domes, October 1972, SECRET, pp. 31-37.

2. J. J. Koelling to R. G. Shreffler, "Environmental Review - PACER," ENG-7-2829, February 7, 1974.

TASK 5.1 : Safety Implications

PROJECT LEADER: LASL, R. G. Shreffler/RDA H. Hubbard

DESCRIPTION :

The feasibility of PACER will depend upon the safety of the system. This task will entail the detailed study of the safety aspects and to ensure that the design of the system meets the applicable safety criterion.

RESOURCES:

DOS-1	Coordination
H-1	Consultation
H-3	Consultation
ENG-6	Consultation
RDA	Consultation

MILESTONES:

7/74	Safety committee formed
12/74	Preliminary draft of safety report

STATUS:

REFERENCE:

TASK 5.2 : Seismic Effects

PROJECT LEADER: LASL, R. G. Shreffler/RDA, H. Hubbard

DESCRIPTION :

This task includes the development and application of codes to calculate the seismic effect of the impulse from the nuclear explosion on all components of the system, as well as ground effects at the surface. The data from the Salmon and Sterling events and the Cowboy series of tests will be evaluated.

RESOURCES:

DOS-1	Coordination
J-9	Research and calculation
RDA	Research and calculation

MILESTONES:

5/74 Preliminary estimates of seismic motions throughout the system.

STATUS:

It has been estimated that the seismic motion at ground surface due to a 420 TJ explosion in the PACER cavity will have the same effect as that due to a 4.2 TJ coupled explosion.

REFERENCE:

RDA October 1973 Progress Report.

TASK 5.3 : Government Safety Regulation

PROJECT LEADER: LASL, R. G. Shreffler/RDA, H. Hubbard

DESCRIPTION :

This task will consist of surveying the various governmental safety and environmental regulations and the respective compliance to these regulations.

RESOURCES:

DOS-1	Coordination
RDA	Coordination

MILESTONES:

STATUS:

Reference 1 has been written.

REFERENCE:

1. J. J. Koelling to R. G. Shreffler, "Environmental Review - PACER," ENG-7-2829, February 7, 1974.

TASK 5.4 : PACER Promotion

PROJECT LEADER: LASL, R. G. Shreffler/RDA, H. Hubbard

DESCRIPTION :

This task has two goals: (1) to present the PACER Program to the people who are responsible for approving and funding the activity, and (2) to present the subject to the public in the best manner. For both goals, this document (references), the RDA proposal (reference 2), and the summary documents will serve as primary sources. As a first step in meeting these goals, a briefing will be prepared for presentation during early April to AEC authorities. The approach for presenting the Program outside the AEC will be developed.

RESOURCES:

DOS-1
RDA

MILESTONES:

3/74 Prepare and schedule briefing at AEC Headquarters. Define tactics for presentation outside AEC.

STATUS:

This project is receiving active consideration.

REFERENCES:

1. DOS-1-81, PACER Program, Phase 1-Theoretical and Laboratory Studies.
2. RDA Proposal 72-26, Electric Power Generation by Thermonuclear Explosives Contained in Salt Domes, October 1973, SECRET.
3. Summary Document (in progress).

PROJECT 6 : Fuel Recovery and Processing

PROJECT LEADER: RDA, Hammond/LASL, A. Nutt

DESCRIPTION:

The capability of continuously removing the small quantities of fission products formed in the cavity will add greatly to the safety and acceptability of the operation, since then only very short-lived activities will be present, and these in extremely dilute form. The problem of design of low cost devices will also be mitigated by the capability of recovering excess primary fuel. The utilization of excess fusion neutrons by capture in thorium or depleted uranium to form ^{233}U or ^{239}Pu will have a pronounced economic value. The project will be accomplished in four tasks, as follows:

Task 6.1 Chemical and physical state of device residues and product in the cavity fluid and interaction with walls and pipes.

Task 6.2 Design and test of equipment for recovery and separation of residues, and for radioactive waste handling and storage.

Task 6.3 Design of equipment and devices for production and recovery of ^{233}U from thorium.

Task 6.4 Design of equipment and devices for production and recovery of ^{239}Pu from depleted uranium.

RESOURCES:

Resources are spelled out with each task.

MILESTONES:

4/74 Project summary completed.

STATUS:

Preliminary calculations have been made showing that the cavity steam flowing to the power plant will contain at most only a few parts per million of solids, and that radioactive contamination of pipes and valves will not prevent maintenance and adjustment if needed. The calculations and physical state studies need detailed refinement, and some experimental confirmation will be desirable.

REFERENCES:

1. RDA Proposal 72-26, Electric Power Generation by Thermonuclear Explosives Contained in Salt Domes, October 1972, Secret, pp. 43-45.

2. See Part II of this document, Experiment 3.

TASK 6.1 : Chemical and Physical State of Suspended Solids in Cavity

PROJECT LEADER: RDA, P. Hammond/LASL, A. Nutt

DESCRIPTION :

Indications are that the residue from the device and any products formed from the subsequent reactions will be finely divided and highly dispersed. The probable chemical state and physical form can be defined by calculation, and some estimates of the rate of agglomeration or plate-out can be obtained. In later phases of the program, some experimental verification of the calculations will be needed to assist in the design of solids recovery equipment and processes. In the experimental phase, some very small-scale dispersions will be created in a steam-filled chamber. Filtering of the steam, both before and after condensing, will provide the debris material for microscopic, chemical,and physical testing.

RESOURCES:

DOS-1	Coordination
WX-2	Research and calculations
RDA	Research and calculations

MILESTONES:

STATUS:

REFERENCES:

1. See Part II of this document, Experiment 3.

TASK 6.2 : Design of Solids Recovery Equipment

PROJECT LEADER: LASL, R. G. Shreffler/RDA, P. Hammond

DESCRIPTION :

It is expected that collection of cavity solids can be best performed on the condensed steam after leaving the primary heat exchanger, where its temperature and pressure are lowest. The design of suitable solids separation process and equipment can be based on known technology, but the necessity of operation in a high-pressure regime and with shielding for the operators requires care and forethought. The equipment will have to be assembled in several parallel streams so that any one line can be serviced while others remain in operation. Processes and equipment for separation of valuable recovered species from radioactive waste will be designed, and procedures for safe conversion and storage of waste will be determined.

RESOURCES:

DOS-1	Coordination
WX-2	Design
CMB-11	Design
H-7	Consultation
RDA	Design

MILESTONES:

STATUS:

REFERENCES:

1. See part II of this document, Experiment 3.

TASK 6.3 : Production and Separation of ^{233}U from Thorium

PROJECT LEADER:

DESCRIPTION :

The physics of the device expansion in the early stages will be studied, to follow neutron temperatures as a function of time and radius. This information will be used to devise the best configuration of ^{232}Th to be placed for best conversion into ^{233}U. The final chemical and physical state will be predicted (and confirmed experimentally in Task 6.1). The separation of recovered ^{232}Th and of produced ^{233}U from the cavity solids collection system will require a detailed chemical processing scheme and specialized process equipment adopted from known technology. Preliminary work can provide process design and cost estimates, but final design must be confirmed by tests on experimental samples.

RESOURCES:

DOS-1	Coordination
WX-2	Design
TD-1	Calculations
TD-3	Calculations
CMB-11	Design
RDA	Calculations and Design

MILESTONES:

STATUS:

REFERENCES:

1. See Part II of this document, Experiment 3.

TASK 6.4 : Production and Separation of ^{239}Pu from ^{238}U.

PROJECT LEADER:

DESCRIPTION:

As in Task 6.3, the best arrangement of depleted uranium in the vicinity of the charge will be calculated; and the conversion processes and economics estimated and designed.

RESOURCES:

DOS-1	Coordination
WX-2	Design
TD-1	Calculations
TD-3	Calculations
RDA	Calculations and Design

MILESTONES:

STATUS:

REFERENCES:

1. See Part II of this document, Experiment 3

PROJECT 7 : Geology, Site Definition and Selection,and Cavity Construction

PROJECT LEADER: RDA, H. Hubbard/D. Rawson; LASL, R. Sharp

DESCRIPTION :

The purpose of this project is to define and assess potential U.S. sites and to generally indicate possible world-wide site potential suitable to the PACER concept; develop site selection criteria related to technical, engineering, economic and environmental trade-offs; select prime site candidates for (1) the scaled field test and (2) the prototype full scale plant (Phase 3); define site exploration methods and requirements; assess the status of cavity construction technology and coordinate planning of the field experiments; and accomplish all aspects of site selection prior to required site confirmation drilling.

Initial engineering, geologic, and economic analyses indicate that massive salt domes or diapir structures are best suited as candidate sites. They have the important properties of deforming plastically rather than with permeable brittle failure at elevated temperatures, have a very low in-situ water content, are water soluble, and are typically unfaulted and relatively homogeneous structures on the scale of tens or hundreds of meters. Of primary concern is cavity stability and its dependence upon shape, pressure and composition of the working fluid, and its response to repeated cycling of stress and thermal conditions. It is, therefore, important that the experimental program develop in close coordination with site criteria, site options, and constraints imposed by real site possibilities.

As a result of past AEC and ARPA projects, there are a great deal of applicable data available from such projects as Gnome, Cowboy, Salmon, Sterling, Payette, and radioactive waste disposal investigations. This information will be reviewed and integrated into PACER site studies to eliminate unnecessary duplication. Salt is also commonly associated with oil and gas accumulations so there exists a vast amount of site geologic, hydrologic, and geophysical data in the public literature and within industry. New salt diapirs are still being located as a result of petroleum exploration. Thus a primary effort, in advance of specific site selection, is a comprehensive literature review. This will cover site possibilities, material properties, and cavity construction technology.

From the literature review there will emerge a number of possible or probable candidates, each with a different amount of existing documentation. Those requiring a minimum of exploration will be given priority to reduce risk associated with exploration costs. The best documented structures are typically being utilized for other purposes so a significant site exploration program may be anticipated. Cost and use sharing with an industry and/or another governmental project will be investigated as part of the site selection process.

The goals of these studies are to anticipate and predict as efficiently and accurately as possible the requirements for determining and ultimately proving out the PACER concept.

RESOURCES:

DOS-1	Coordination
J-9	Geology and Engineering
J-7	Engineering
J-6	Construction and Geological Engineering
ENG-6	Engineering
RDA	Geologic Consultation and Engineering

MILESTONES:

4/74 Initial summary report - summarizing work in progress covering literature review and analysis, and discussions with key investigators in the following areas:

1. Distribution, geologic setting, and associated potential site characteristics of U.S. salt diapir structures.
2. State-of-the-art in solution mining of large cavities in salt and their dependence upon salt properties and other site characteristics.
3. World-wide salt diapirs as potential locations for the PACER concept.
4. Salt physical and chemical properties related to cavity stability.

From this review, initial site selection criteria will be established, exploration methods discussed, input for laboratory experiments will be provided, and a preliminary list of candidate sites will be developed.

7/74 Progress Report - Describing result of continued literature review, discussions with key investigators, and preliminary examination of several possible field sites. The initial field examinations will also include obtaining data on land ownership and acquiring geologic and geophysical data locally from industry and governmental agencies.

Project 7

10/4	Progress Report - Complete definition of site selection criteria and literature review, narrow list of candidate sites for the PACER field tests and pilot plant, and initial description of exploration requirements for the different specific sites. Considerable travel will be required.
1/75	Final Report of the preliminary site selection phase with recommendations, exploration methods and estimated costs required for final site selection and cavity excavation.
7/75	Progress Report resulting from analysis of existing or obtainable geophysical data and a limited amount of newly acquired geophysical data to further define the final sites. Required confirmatory drilling is not included.
1/76	Site(s) selected with exploration for the 1/100th Scale PACER experiment completed except for drilling and associated bore-hole studies.

STATUS:

A large collection of referenses is being gathered and reviewed for preparation of the April 1974 Summary Report. At present it appears that there are about 175 sites requiring further evaluation as potential sites for application of the PACER concept. Of these sites, perhaps a dozen will be sufficiently well documented to qualify as primary site candidates. The U.S. sites appear to be restricted to the interior and coastal basins of East Texas, Louisiana, Mississippi and Western Alabama. A few are located off-shore of the Gulf Coast. Other sites are located in the Phoenix-Kingman area of Arizona and in the Paradox basin of Utah and Colorado.

REFERENCES:

1. RDA Proposal 72-26, October 1972, Electric Power Generation by Thermonuclear Explosions Contained in Salt Domes. Secret.
2. Baidyuk, B. X., 1967, Mechanical Properties of Rocks at High Temperatures and Pressures, Consultants Bureau, New York, 75 pp.
3. Such as: Rawson, D., Randolph, P., Boardman, C., and Wheeler, V., 1965, Post-explosion Environment Resulting from the Salmon Event, UCRL-14280, Livermore, CA, 31 pp., and Sisemore, C., Rogers, L., and Perret, W., 1969, Project Sterling; Subsurface Phenomenology Measurements Near a Decoupled Nuclear Event, J. Geophys. Res., J. 74, p. 6523-6637, etc.
4. Borchert, H. and Muir, R., 1964, Salt Deposits, the Origin, Metamorphism and Deformation of Evaporites, D. VanNostrand Co., Ltd., New York, 338 pp.
5. Braitsch, O., 1971, Salt Deposits, their Origins and Composition, Springer-Verlag, New York, 297 pp.

6. Goguel, J., 1962, Tectonics, Eng. Trans. from French Ed. of 1952, W. H. Freeman and Co., San Francisco, 384 pp.

7. Hawkins, M. and Jirik, C., 1966, Salt Domes in Texas, Louisiana, Mississippi, Alabama, and Offshore Tidelands: A Survey, U.S. B. Mines Inf. Circ. 8313, 78 pp.

8. For instance, see Halbouty, M., 1967, Salt Domes, Gulf Region - United States and Mexico, Gulf Publishing Co., Houston, 425 pp.

9. Nettleton, L., 1955, History of Concepts of Gulf Coast Salt-Dome Formation, Am. Assoc. Petrol. Geol. Bull., V. 39, p. 2373-2384, and, Halbouty, M. and Hardin, G., Jr., 1956, Genesis of Salt Domes of Gulf Coastal Plain, Am. Assoc. Petrol. Geol. Bull., V. 40, p. 737-746.

10. For instance, see Balk, R., 1953, Salt Structure of Jefferson Island Salt Dome, Iberia and Vermilion Parishes, Louisiana, Am. Assoc. Petrol. Geol. Bull., V. 37, p.2455-2474, and Kupfer, D., 1962, Structure of Morton Salt Co. Mine, Weeks Island Salt-Dome, Louisiana, Am. Assoc. Petrol. Geol. Bull., V. 46, p. 1460-1468.

11. Clabaugh, P., 1962, Petrofabric Study of Deformed Salt, Science, V. 136, p. 389-391.

12. Dreyer, R., Garrels, R., and Howland, A., 1949, Liquid Inclusions in Halite as a Guide to Geologic Thermometry, Am. Mineralogist, V. 34, p. 26-34.

13. Hoy, R., Foose, R., and O'Neill, B., Jr., 1962, Structure of Winnfield Salt Dome, Winn Parish, Louisiana, Am. Assoc. Petrol. Geol. Bull., V. 46, p. 1444-1460.

14. Fenix and Scisson, Inc., 1969, Project Payette, Final Summary Report, USAEC, Las Vegas, Nev., 42 pp.

15. See Part II of this document, Experiments 2, 4, 5, 6, 8, 9, 10.

PROJECT 8 : Feasibility Study for Nuclear Test and Effects Facility

PROJECT LEADER:

DESCRIPTION :

It has been proposed (reference 1) that the principles and techniques developed in the PACER program could be applied to the development of a nuclear test and effects site that, if proven feasible, might have certain advantages:

- The safety of the facility would be assured by its existence in a stable homogeneous medium, by a thoroughly understood cavity and environmental phenomenology, and by well engineered hardware. These features might not only afford assurance against gross accidents, they might reduce to an acceptable level the possibility of escape of any radioactive products.
- The facility could be permanent and used frequently. It would require minimum ground surface area. Permanent, well calibrated tools could record the results of nuclear tests.
- Because of the highly decoupled explosion and the reasonably small facility, the effect on the environment and the community should be minimal.
- The highly decoupled system could be an advantage if we were confronted with a test ban that imposed restrictions based on seismic levels. In fact, the possibility of such a facility (plus other factors) raises the question as to whether any kind of a test ban can be technically significant.
- The initial cost for this facility would be significant, but total costs over a long period of time could be much less than we presently expend for underground testing. For example, if feasible for high enough yields, we would need to drill no more holes; the security and labor force could be drastically reduced, and one would anticipate fewer labor disputes; the logistics and duplication of instrumentation could be minimized.

It should be noted that nuclear tests have been fired in cavities in the past. Sterling is an example of a low yield (380 tons) test in a salt dome cavity. Cannikin, although not effectively decoupled, is an example of a much higher yield experiment done in a mined cavity and accompanied by complex diagnostics.

The definition of a test site would follow closely the outline of the PACER program as stipulated in the first seven Projects of this document. The amount of effort required would depend upon the effort already incorpoated into PACER.

The specific tasks defining this project are the following:

Task 8.1 Project Planning and Coordination
Task 8.2 Cavity Phenomenology
Task 8.3 Engineering
Task 8.4 Nuclear Test and Effects Diagnostics
Task 8.5 Safety and Environmental Considerations
Task 8.6 Site Definition, Selection, and Cavity Engineering
Task 8.7 Cost

RESOURCES:

The resources are spelled out with each of the tasks. It should be noted that the capabilities of both RDA and LASL are admirably suited for such a project. At LASL a large share of responsibility will reside in J Division.

STATUS:

Reference 2 proposes that Reference 1 serve as a point of departure for the development of a nuclear testing facility. It requests that "the FY 75 PACER activities include specific studies on the technical feasibility, utility, economics, safety, and environmental impact of such a facility. These should be defined in sufficient detail to permit appropriate evaluation by DMA and should include both development and effects testing aspects. The proposal should be received in Headquarters by May 1, 1974." As a consequence of reference 5 priority of this project has been reduced to a low and undetermined level in FY 75.

Reference 3 documents intended LASL/RDA opinion and proposed activity on this project.

All group leaders have been contacted and estimated manpower inputs received.

REFERENCES:

1. The Association of the PACER Program and tne Nuclear Weapons Program, DOS-1-82, November 29, 1973, Harmon Hubbard and R. G. Shreffler.

2. F. C. Gilbert to H. M. Agnew, Letter dated February 7, 1974.

3. R. G Shreffler to F. C. Gilbert, Letter dated February 15, 1974.

4. For associated experiments see the corresponding tasks of PACER.

5. J6-74-65, Group Estimates of Manpower Requirements for One Year Feasibility Study of a Reusable Nuclear Test and Effects Facility as Proposed in PACER Project 8.

TASK 8.1 : Project Planning and Coordination

PROJECT LEADER:

DESCRIPTION :

The purpose of this task is to plan, coordinate, and report on the progress of this project. A primary function will be to establish criteria for the various tasks. Such parameters as test yield limitations, test frequency, and seismic decoupling factor must be established. Operating procedures and site specifications will be defined. Safety and security will be given primary consideration.

RESOURCES:

DOS-1	Coordination with rest of PACER
J-DO	Planning and coordination of Project 8
J-6	Collection and assimilation of data from J Division groups.
RDA	

STATUS:

All Group Leaders at LASL have been contacted and estimated manpower inputs received.

REFERENCES:

1. J6-74-65, Group Estimates of Manpower Requirements for One Year Feasibility Study of a Reusable Nuclear Test and Effects Facility as Proposed in PACER Project 8.

TASK 8.2 : Cavity Phenomenology

PROJECT LEADER:

DESCRIPTION :

The following subjects will be addressed.

1. A selection of the cavity size and depth consistent with choices made in Task 8.1.
2. An investigation of the effects of the nuclear explosion (t < 1 sec).
3. Determination of teleseismic signal decoupling over a range of parameters.
4. An investigation of the feasibility of cavity reusability.
5. Investigation of cavity stability.

To a large degree this task will employ the techniques and results generated by Project 2, Cavity Phenomenology.

RESOURCES:

DOS-1	Coordination
J-10, J-15, T-4	Investigation of nuclear explosion (t<1 sec).
J-9	Determination of teleseismic signal
T-3	Investigation of nuclear explosion (t>1 sec).
J-6	Investigation of cermets and grouts to withstand effects at cavity boundary.
J-7	Investigation of materials and designs to withstand effects at cavity boundary.
J-8	Electronics support to J-9 investigations.
RDA	

STATUS:

REFERENCES:

See documents listed under Tasks of Project 2.

TASK 8.3 : Engineering

PROJECT LEADER:

DESCRIPTION:

This task will consider all the engineering except for the mining of the cavity. This will include the surface installation, the pipes and cabling connecting the surface with the cavity, the cassette containing the test device and instrumentation, the equipment for lowering the cassette, and any device used for cooling the cavity. At the present time it is difficult to carry the description of the engineering much further. Tasks 8.1 and 8.2 must proceed to better resolve a description of the site.

RESOURCES:

J-6	Civil and coordination
J-7	Mechanical
J-8	Electrical
J-9	Design input
J-12	Design input
J-14	Design input
J-16	Design input
CNC-11	Design input
RDA	

STATUS:

REFERENCES:

1. See Project 3, this report.

TASK 8.4 : Nuclear Test and Effects Diagnostics

PROJECT LEADER:

DESCRIPTION:

The purpose of this task is to select the best diagnostic techniques. It is probable that most instrumentation will be included in a cassett which also contains the nuclear device. At the outset it is not obvious how radiochemistry can be used. Reliance must be shifted to first sampling and dependence on short half-lived isotopes. This difficulty may be furthe compensated by the validity associated with blast and flux (γ and η) measurements in the homogeneous cavity media.

Equal priority will be given to the execution of effects tests. This would include the configuration of typical experiments along with instrumentation. An attempt should be made to design methods for exposure followed by recovery.

RESOURCES:

CNC-11	Radiochemical Analysis
J-8	Electronics Support
J-9	Predictions
J-10	Predictions
J-12	PINEX, etc.
J-14	Yield measurements
J-15	Effects predictions
RDA	

STATUS:

Preliminary talks have been held

REFERENCES:

TASK 8.5 : Safety and Environmental Considerations

PROJECT LEADER:

DESCRIPTION:

Safety is the watchword of this project. In many regards the project has advantages from the safety point of view:

- The installation is installed in a relatively homogeneous medium, the behavior of which will be carefully studied.
- The explosions will be highly decoupled giving minimum insult to the cavity walls and the hardware.
- The hardware is permanently installed; it is carefully and conservatively engineered; it is sealed to reduce to an acceptable level any leakage to the surface.

The specific definition of the safety problem will depend upon a description of the system as developed under Tasks 8.1, 8.2, and 8.3.

The following four sub-tasks must be considered:

- Examine each aspect of the concept and design for the safety implications.
- Resolve to a sensible degree the expected seismic effects of the nuclear explosion upon all the mechanical components of the system, and the effects at the surface of the ground.
- Investigate the legal implications of the project from the safety point of view.
- Resolve how and when project should be presented to the public.

MILESTONES:

RESOURCES:

J-1
J-6
J-7
J-8
J-9
J-10
J-15
H-1
CNC-11
RDA

STATUS:

Same

REFERENCES:

TASK 8.6 : **Site Definition, Selection, and Cavity Engineering**

PROJECT LEADER: RDA, Rawson/LASL, Sharp

DESCRIPTION:

In practically all respects this task is identical with PACER Project 7.

MILESTONES:

RESOURCES:

J-6	Field surveys
J-9	Geophysical studies
RDA	

STATUS:

REFERENCES:

TASK 8.7 : Cost

PROJECT LEADER:

DESCRIPTION:

The cost of the project will be estimated. This will include the capital investment, the operating cost, and the cost incurred in the execution of a nuclear test. Much of this information will be available from the other projects of the PACER program.

MILESTONES:

RESOURCES:

DOS-1
J-6
J-7
J-8
J-9
J-12
J-14
J-15
J-16
H-1
RDA

STATUS:

REFERENCES:

PROJECT 9: : System Analysis, Coordination and Planning

PROJECT LEADER: LASL, Shreffler/RDA, Hubbard

DESCRIPTION:

Because of the complexity of the PACER system it must be subjected to continuing analysis as new ideas or designs are incorporated. This activity is necessary to insure compatibility, not only of system elements, but of operational procedures as well. The entire system--from explosive manufacture and assembly to waste disposal--must be thought through and integrated. To achieve this goal, careful coordination and management of all on-going activities is essential.

The PACER program is divided into three phases. The program for the first phase is defined in this document. Subsequent documents will be prepared defining the plans for the remaining two phases. The reasons for the preparation of these documents is spelled out in the introduction.

This initial phase will be subjected to continuing scrutiny. The tasks and experiments will be defined in more detail. Priorities will be established in order to anticipate various levels of annual funding.

RESOURCES:

RDA Harmon Hubbard plus RDA staff
LASL R. G. Shreffler plus LASL staff

MILESTONES:

4/74 This document completed.

STATUS:

A great deal of time has been devoted in the first fiscal year to planning the program as outlined in this document.

REFERENCES:

1. Form 189a (in progress).

PACER PROGRAM

Part 1 - Theoretical and Laboratory Studies

Part II, Experimental Program

The Phase 1 experimental effort of the PACER Program is defined in this part of the document. The following table is a summary list of experiments along with their cost. A reasonable time for their execution is estimated to be about three years.

PACER Phase 1 Experimental Program

Exp't No.	Experiment Name	Total Cost ($K)
1	Material Selection	217
2	Halite Creep Rupture Experiments	77
3	Primary Loop Mockup	918
4	Shaft Sealing	728
5	Device Injection	678
6	Dynamic Loading of Access Piping	703
7	Steam-Cavity Wall Interaction	81
8	Laboratory Cavity Experiment	835
9	Anhydrite Creep Experiment	77
10	Radiation Deposition in Salt	100
		$ 4414

Although a considerable amount of effort has been devoted to the definition of these experiments, it is recognized that others may be added, and certainly the descriptions will become more complete, and the costs more realistic.

EXPERIMENT # : 1

NAME : Material Selection

PROJECT LEADER : N. Kfoury (RDA)/A. Nutt (LASL)

PURPOSE : The purpose of this experiment is to determine the corrosion behavior of candidate PACER alloys for operating environments.

TASKS : 2.1, 3.1.2, 3.1.3, 3.1.4, 3.1.7, 3.2, 4.2, 5.1

DESCRIPTION :

Corrosion is the destruction of metal or alloy by chemical change, electrochemical action, or physical dissolution. Erosion is the destruction of a metallic object by mechanical processes in the absence of chemical attack. When corrosion and erosion operate simultaneously, conjoint action, the damage produced far exceeds the effect of either operating independently.[1] A type of conjoint action that denotes cracking caused when a steady tensile force acts upon a metal in a corrosive environment is called stress corrosion cracking. When stress corrosion cracking results from cyclic stress applications in a corrosive environment, the combination is referred to as corrosion fatigue. Cracking caused by stress corrosion or corrosion fatigue may propagate via grain boundaries (intergranular cracking) or may propagate across individual grains (transgranular cracking). Destructive attack occurring over a large portion of the exposed surface is termed general corrosion; destructive attack occurring only in small isolated areas of exposed surface is termed localized corrosion; and destructive attack confined to small points in the exposed surface is termed pitting.

The objective of this project is to study the corrosion behavior of candidate PACER piping materials exposed to a halite-anhydrite-water environment at the proposed operating temperature and pressure (525°C and 320 bars). Metallic stress states similar to those expected under field conditions will be exposed and studied. Annealed, cold worked, and welded samples will be tested on a long term (2 yr) and a short term (3 mo) basis. Stress corrosion cracking will be investigated using testing concepts reviewed by H. P. Godard and J. J. Harwood.[2] The extent of corrosion will be determined metallographically and corrosion products will be identified using x ray and microprobe analyses, and corrosion kinetics will be inferred using proven microbalance techniques. Definition of the most promising candidate materials will be made.

MILESTONES:

April 1974	Selection of preliminary candidate materials based upon literature searches, industrial suggestions, and static corrosion tests.

MILESTONES (Cont'd):

July 1974	Begin long term static corrosion studies on the most promising candidate materials. Begin stress corrosion studies.
August 1974	Report selecting candidate piping materials based upon short term corrosion effects.
November 1974	Report updating and comparing static corrosion and stress corrosion data.
December 1974	Begin turbulent corrosion studies in the engineering test loop (Experiment #3).
April 1975	Summary report on short term and intermediate term testing corrosion data.
April 1976	Summary report of two years of PACER corrosion studies.

RESOURCES:

DOS-1	Coordination
WX-2	Consult and Execute experiment
RDA	Consultation

FACILITIES

No special facilities are needed. All work can be accomplished with existing equipment. $1500 capital monies include a pressure readout DVM and a $300 furnace. The DVM can probably be borrowed from another LASL group, but the source is not yet known. The furnace can be fabricated under M&S for about twice the capital expense.

STATUS:

Preliminary testing has shown that a series 18 and 8 stainless steel (316) forms a blue colored layer on its surface when exposed to a H_2O + NaCl atmosphere at 525°C and 360 bars for 24 h. X-ray patterns have been made, but the corrosion layer has not been identified.

A three week exposure of a 316 series stainless steel to a H_2O-NaCl atmosphere at 575°C and 370 bars produced massive corrosion of the steel specimen. However, the bomb containing the specimen (also 316 steel) was badly oxidized and a leak may have occurred. The test is being repeated.

STATUS (cont'd)

Samples of Inconel Alloy 625 have been received. Hastelloy C-276 samples are expected in the near future, at which time corrosion testing of Ni-based alloys will begin.

REFERENCES:

1. Evans, U.R., The Corrosion and Oxidation of Metals, St. Martins Press, New York, 1960.

2. Godard, H. P. and Harwood, J. J., "Some Remarks on Stress Corrosion Testing," An Educational Lecture, Corrosion, 11, 93t-985, Feburary 1955.

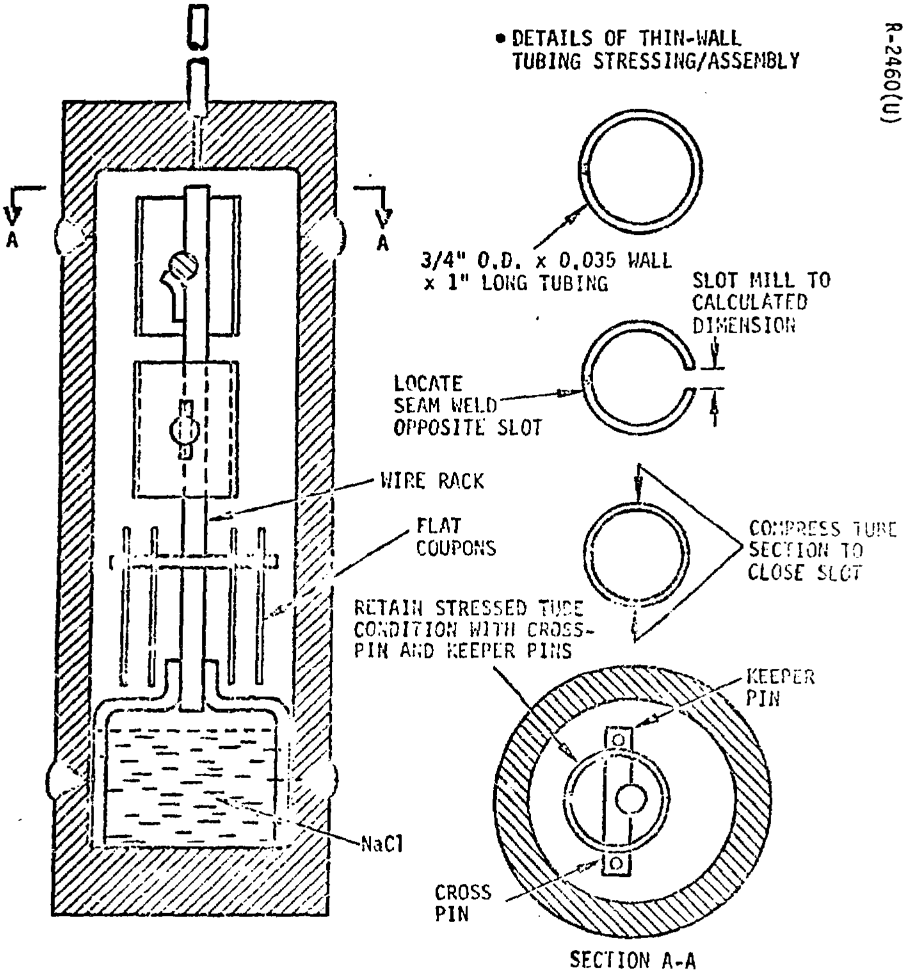
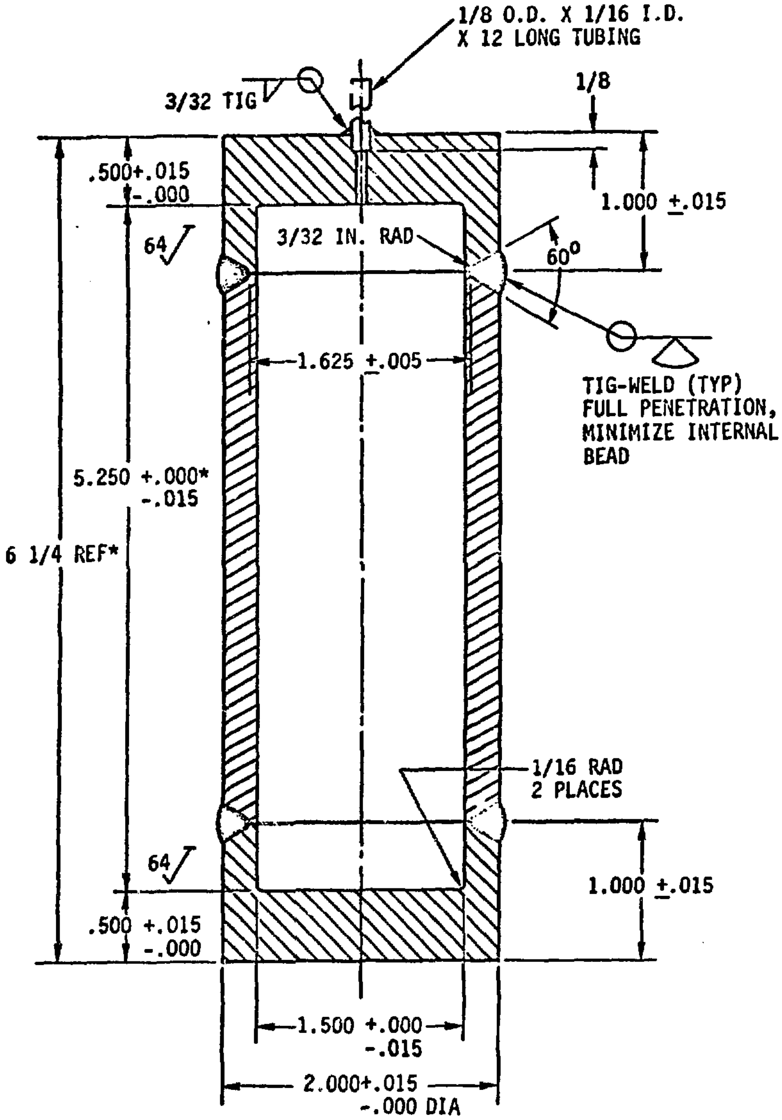


Figure 1. Test Specimen Assembly



*DIMENSIONS BEFORE WELDING

Figure 3. Test Capsule

EXPERIMENT NO : 2

NAME : Halite Creep Rupture Experiments

PROJECT LEADER : LASL, C. A. Anderson/RDA, A. Fields

PURPOSE : The purpose of this experiment is to determine the creep rupture behavior of halite at temperatures and stress states typical of PACER operating conditions.

TASKS : 2.4

DESCRIPTION :

Creep rupture concerns the deterioration of materials with time as a result of time dependent stress or deformation. Creep rupture can be either ductile (failure caused by reduction to zero of load carrying area) or brittle (failure caused by the formation and spreading of cracks) in nature. Theories to handle the phenomena of ductile and brittle creep rupture for situations of uni-axial tensile stress were advanced originally by Hoff (1) and Kachanov (2), respectively. Extensions of these theories to situations of multi-axial stress characteristic of underground cavities have occurred only recently (3) with the primary difficulty being that of determining the "controlling stress quantity."

The object of this experiment is to support ongoing calculations on the stability of the PACER cavity by providing experimental data on the rupture characteristics of halite at temperatures near 500°C and average confining pressures of 320 bars. Initial experiments will be carried out on cylindrical specimens of halite at the above static confining pressure but with a reduced value of the axial compressive stress. Using values of the axial stress between zero and 300 bars, the time to rupture and the permanent tensile strain at rupture of each sample will be recorded. After the completion of the initial experiments an additional set of experiments on halite samples with the same confining pressure and temperature will be carried out but now with a time dependent cyclical axial pressure variation characteristic of cavity pressure swings. Again, rupture time and permanent strain at rupture will be to the variables of interest.

The experimental creep rupture data can be folded into the cavity stability calculations in the following fashion. We first select a controlling stress, probably the maximum principal tensile stress difference, and locate those positions on cavity surface which have maximum values of the controlling stress as indicated by the calulational model. The time variation of the controlling stress can also be described by the calculational model, and by replacing the continuous time variation of the controlling stress by a

DESCRIPTION (Cont'd):

piecewise constant controlling stress, one can use the experimental data to predict when rupture occurs. This procedure is described in (4).

MILESTONES:

We do not anticipate beginning creep rupture experiments on halite until the cavity stability calculations (for both transient and steady state conditions) have been completed (July 1974). We anticipate a project duration of about two years concluding with a summary report on halite creep rupture behavior at elevated temperatures.

RESOURCES:

DOS-1	Coordination
WX-3	Consult and execute experiment
RDA	Consult

FACILITIES REQUIRED:

Halite samples will be fabricated from commerically pure NaCl using LASL's explosive pressing facilities. Group WX-3 (LASL) has already allocated funds for purchase of an MTS system to be installed by July 1974. This system allows for accurate load control and could be used to control both axial load and confining pressure on the halite samples. In addition, this MTS system would allow the application of a time dependent axial load. The only additional equipment required for completion of these experiments would be a fixture to contain the specimen and an oven capable of reaching and holding a temperature of 500°C.

STATUS:

REFERENCES:

1. Hoff, N.J., The Necking and Rupture of Rods Subjected to Constant Tensile Stress," JAM, Vol. 20, 1953.

2. Kachanov, L.M., Izv. Akad Nauk, USSR, No. 8, <u>26</u>, 1958.

3. Odquist, F.K., <u>Mathematical Theory of Creep and Creep Rupture,</u> Oxford Math Monographs, Clarendon Press, 1966.

4. K. Nair and R. D. Singh. Creep Rupture Criteria for Salt. Paper Prepared for the 4th Sympusium on Salt, Houston, Texas, April 15-18, 1973.

CWL 1/15/74

EXPERIMENT # : 3

NAME : Primary Loop Mockup

PROJECT LEADER: LASL, T. Merson/RDA, L. Gore

PURPOSE : One of the major engineering problems of PACER involves the design of the primary loop for transporting hot steam from the cavity to the heat exchangers and back to the cavity. The fluid is expected to be saturated with salt in the cavity at 0.03% salt and could give up its salt content in the upcommer or throttle valve as equilibrium concentrations of salt in the steam downstream of the throttle is near 0.015%. One primary purpose of this test is to study the salt transport problem including functional effects on valves, heat exchanger surfaces, pumps, etc. Another purpose of this test is to gain experience in other engineering areas such as materials and corrosion with actual samples of salt dome salt. It could well develop that a test loop similar to the one proposed could be used to evaluate the effects of salt from various salt domes (and hence composition variations) to aid in establishment of dome selection criteria. Deposition of explosive debris throughout the loop will also be investigated. Methods for removing such materials as plutonium, uranium, fission products, and other debris from the stream will be investigated.

TASKS : 2.1, 3.1, 3.2, 3.3, 3.4, 6.1, 6.2, 6.3, 6.4.

DESCRIPTION :

A schematic of the test loop is shown in the figure. The essential features include:

- A sample of salt dome salt in a heated cavity.
- A throttle valve and heat exchanger.
- A test section which can be used to study corrosion of materials.

Heated steam passes through a salt storage volume. The salt laden steam passes through a test section and throttle valve that simulates the upcommer steam pipes. A heat exchanger section cools the steam and provides a test of exchanger performance and scale buildup. A pump to circulate the water through the heater and back to the cavity completes the loop. Sample ports allow chemical analysis of the steam and the ability to add various materials. A test chamber in the hot steam line can be used to study the effect of the moving working fluid on corrosion, etc., of various metal samples.

FACILITIES:

This experiment will require a shop facility and a test cell to protect against the high pressure and temperature of the working fluid. The capability of chemically and physically analyzing and recording the history of the experiment will be required.

MILESTONES:

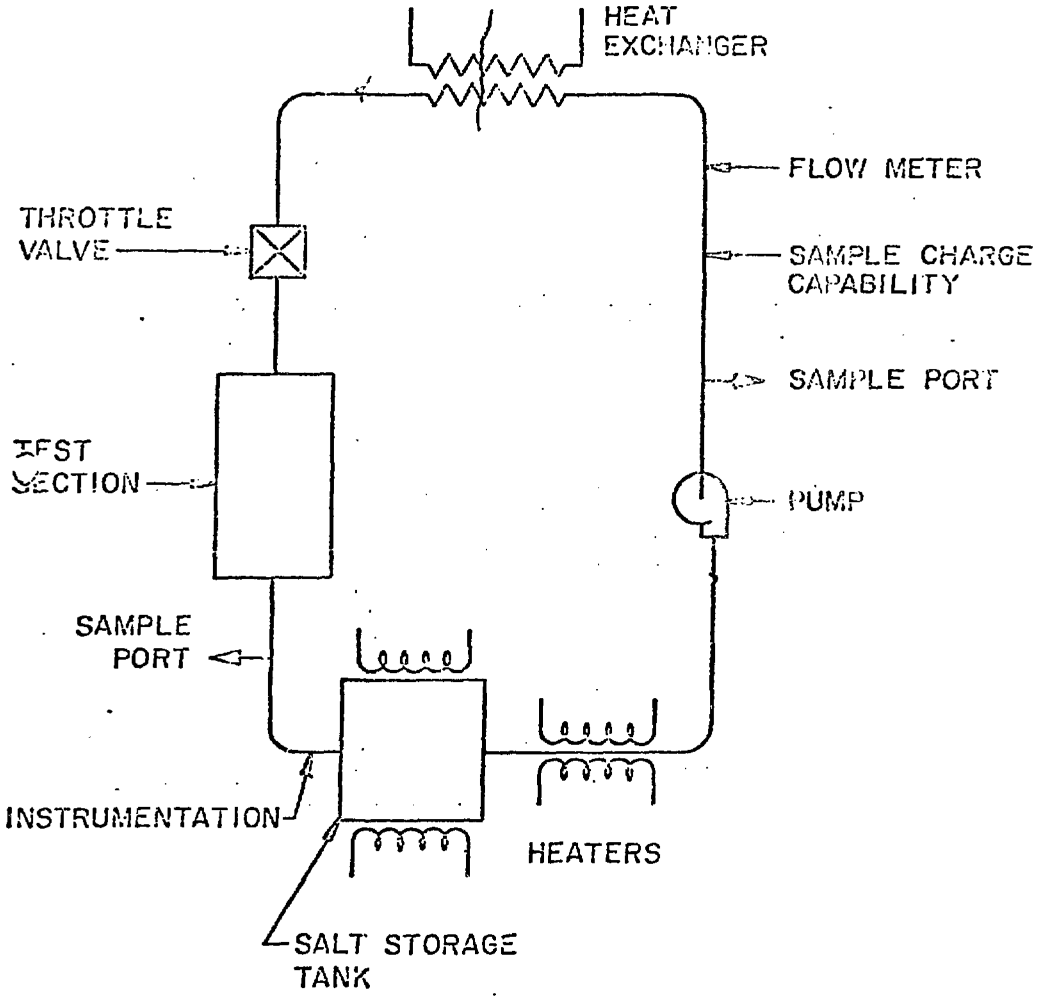
3/74	The experiment will be analyzed and developed in detail. This experiment will require 3 years to complete on a reasonable schedule. It may be desirable to continue the experiment at some level of effort indefinitely.

RESOURCES:

DOS-1	Coordination
ENG-6	Consult and execute experiment
WX-2	Consultation
RDA	Consultation

STATUS:

REFERENCES:



SALT TRANSPORT SIMULATION LOOP

EXPERIMENT # : 4

NAME : Shaft Sealing

PROJECT LEADER: **LASL, T. Merson/RDA, L. Gore**

PURPOSE : The purpose of the shaft sealing test program is to study on a laboratory scale the sealing around the pipe o.d. This is necessary to prove that cavity access can be accomplished without allowing the cavity fluid to leak. Various types of sealing mechanisms will be studied and the effect of shaft temperature and salt creep should be included. Relative movement of salt and shaft during startup and shutdown will be considered.

TASKS : 3.1, 3.4, 5.1

DESCRIPTION :

The proposed test fixture (see figure) should allow investigation of many design questions. Specific features include:

- A pressure vessel
- A block of salt.
- Pressure plenna that can be pressurized independently and used to measure leak rates.
- A shaft which can be pressurized and loaded axially.
- Heating cooling elements to simulate thermal effects.
- A mechanical seal testing area for mechanical seals of various designs.
- A capability for seal testing under relative motion of salt and shaft.

The test program could map leak rates as a function of shaft length, pressure levels, creep time, etc. With only slight modification, one could study grouting or a variety of mechanical sealing designs for effectiveness. By using tubing of different size and axial loading, much information on the salt/shaft interface could possibly be obtained.

MILESTONES:

3/74 Experiments rewritten in light of further considerations.

RESOURCES:

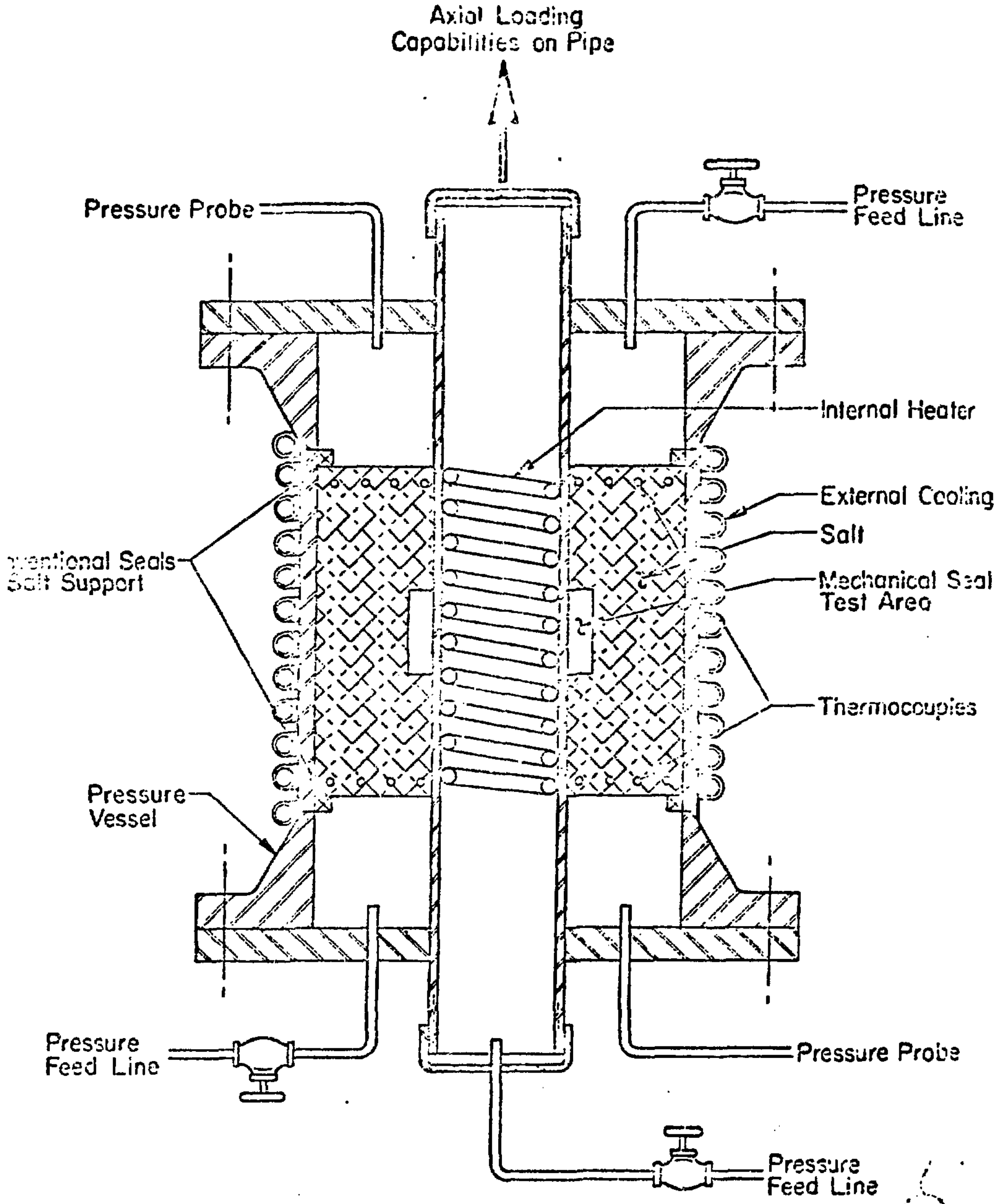
DOS-1	Coordination
ENG-6	Plan and execute experiment
J-9	Consultation
J-6	Consultation
RDA	Consultation

FACILITIES:

A test cell meeting the high experimental temperature and pressures is required along with appropriate sensing and recording equipment, and a shop facility.

STATUS:

REFERENCES:



Shaft Sealing Test Apparatus

EXPERIMENT # : 5

NAME : Device Injection

PROJECT LEADER: LASL, T. Merson/RDA, L. Gore

PURPOSE : Laboratory testing of one or more designs of the injection system will be required. Specifically, the concepts will require definition, and the system will need development testing to determine leak rates and demonstrate reliability.

TASKS : 3.1, 3.4, 3.5, 5.1

DESCRIPTION :

Device injection concepts should be developed consistent with well considered design constraints. Models will be constructed. Scale system(s) will be tested under realistic working pressures and temperatures. A selected design will be studied for possible testing in full scale diameter with actual hardware.

MILESTONES :

3/74 The experiment will be rewritten in light of further considerations and the completion of Reference 2.

RESOURCES:

DOS-1	Coordination
ENG-6	Plan and execute experiment
J-9	Consultation
J-6	Consultation
RDA	Consultation

FACILITIES:

This experiment will require a test cell, shop facilities and appropriate instrumentation.

STATUS:

REFERENCES:

1. Preliminary Thoughts on Device Injection for PACER, ENG-6-132, Dec. 6, 1973
2. Constraints on PACER Device Injection (in progress).

EXPERIMENT # : 6

NAME: : Dynamic Loading of Access Piping (Wall Shock Experiment)

PROJECT LEADER:

PURPOSE : A major engineering problem inherent with the PACER concept is the effect of shock loading from the explosions on the access piping. Specific questions that need attention are:

0 Is the shock transmitted up the piping stem to affect performance or reliability of pumps, valves, seals and heat exchangers?

0 Is there any danger that shock loading from the explosions could damage the access piping?

0 Does the presence of the shaft penetration in the cavity wall cause local stress patterns which could cause progressive cavity damage?

TASKS : 2.2, 2.4, 3.1, 3.2, 3.3, 3.4, 3.5, 5.1.

DESCRIPTION :

A schematic of one test apparatus is shown in the figure. The essential features of the apparatus are:

0 A cylindrical geometry that can be impacted with a one-dimensional shock from a shock generated in the working fluid.

0 A mockup of a cavity access pipe surrounded by salt.

0 A pressure vessel to simulate the rigidity of the salt dome.

0 All elements will be sustained at the temperature and pressure characteristic of the cavity.

Using these arrangements, the effect of explosions on the access piping engineering can be studied and competing design concepts can be evaluated. This experiment will be preceded by a careful analysis to explore its validity, to elaborate the details, and to modify and extend the experiment.

MILESTONES:

3/74 This experiment will be written in light of more careful analysis.

RESOURCES:

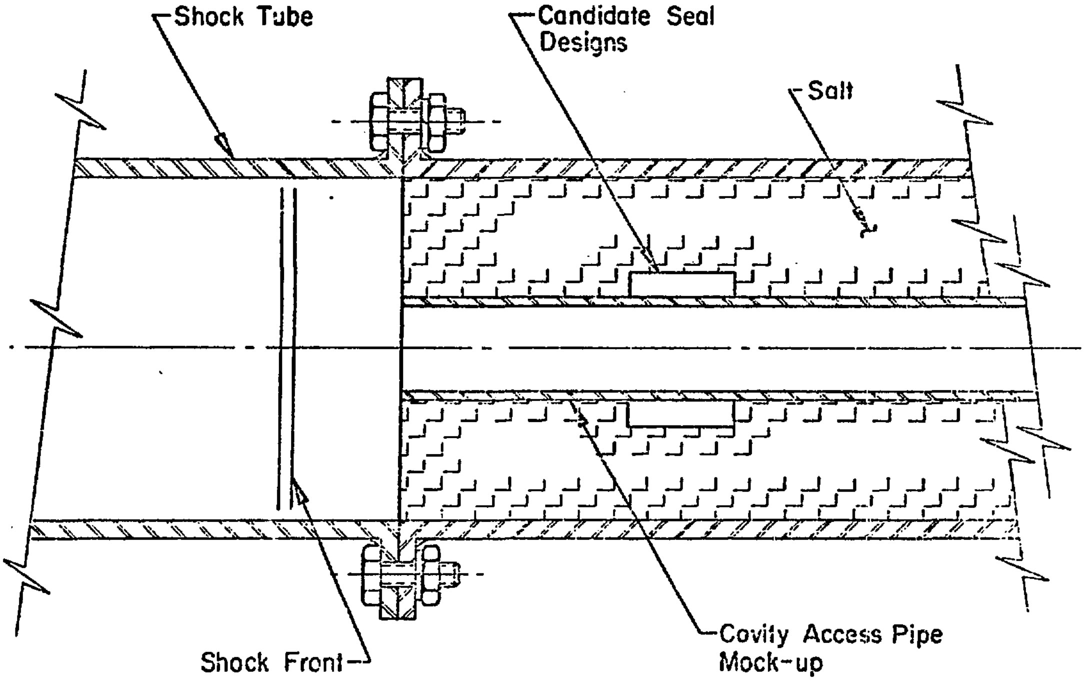
DOS-1	Coordination
M-6	Plan and execute experiment
ENG-6	Consultation
J-6	Consultation
RDA	Consultation

FACILITIES:

This experiment will require a test cell, shop facilities, and appropriate instrumentation.

STATUS:

REFERENCES:



Experimental Schematic of Dynamic Loading of Cavity Access Piping Using a Shock Tube

los alamos
scientific laboratory
of the University of California

EXPERIMENT # : 7

NAME : Steam-Cavity Wall Interaction Experiments

PROJECT LEADER: S. Ridgway (RDA)/A. Nutt (LASL)

PURPOSE : The purpose of this experiment is to study the phenomenology of the interaction of steam with defects in a salt wall at low temperatures and pressures preliminary to the high temperature and pressure studies.

TASKS :

DESCRIPTION :

There are several possibilities for the cavity wall to be attacked by solution in the cavity steam. The general method of protection of the wall is to keep the salt that is in contact with the steam hot enough so there is no stable liquid phase at the operating pressure. If there were a crack or other defect in the wall that allowed the steam to penetrate and reach salt cool enough so that the steam could condense to a liquid phase that would contain about 50% salt, there is a mechanism for such a defect to grow at a rate that would be determined by the ability of the salt to conduct the heat of condensation away. It is important to learn as early as possible whether such defects will heal, grow to a certain size, or grow indefinitely.

Since the rate limiting step seems to be the conduction of the heat of condensation of the steam through the salt, experiments with steam at approximately atmospheric pressure, and blocks of salt with temperature spans from 120 to 50°C should be instructive and meaningful.

Blocks of salt will be exposed to low pressure steam with the salt face being at a temperature above the liquid phase condensation temperature, and the block interior at a tempeature below the condensation temperature. Various defects will be introduced into the face of the block to allow steam communication to the colder center, and the development of the defects observed.

MILESTONES:

April 1974	Conduct preliminary uninstrumented tests, and design laboratory test setup.
June 1974	Design laboratory test sstup.
February 1975	Summary report on solution effects at low temperature and pressure.

RESOURCES:

LASL	WX-2
RDA	Facilities

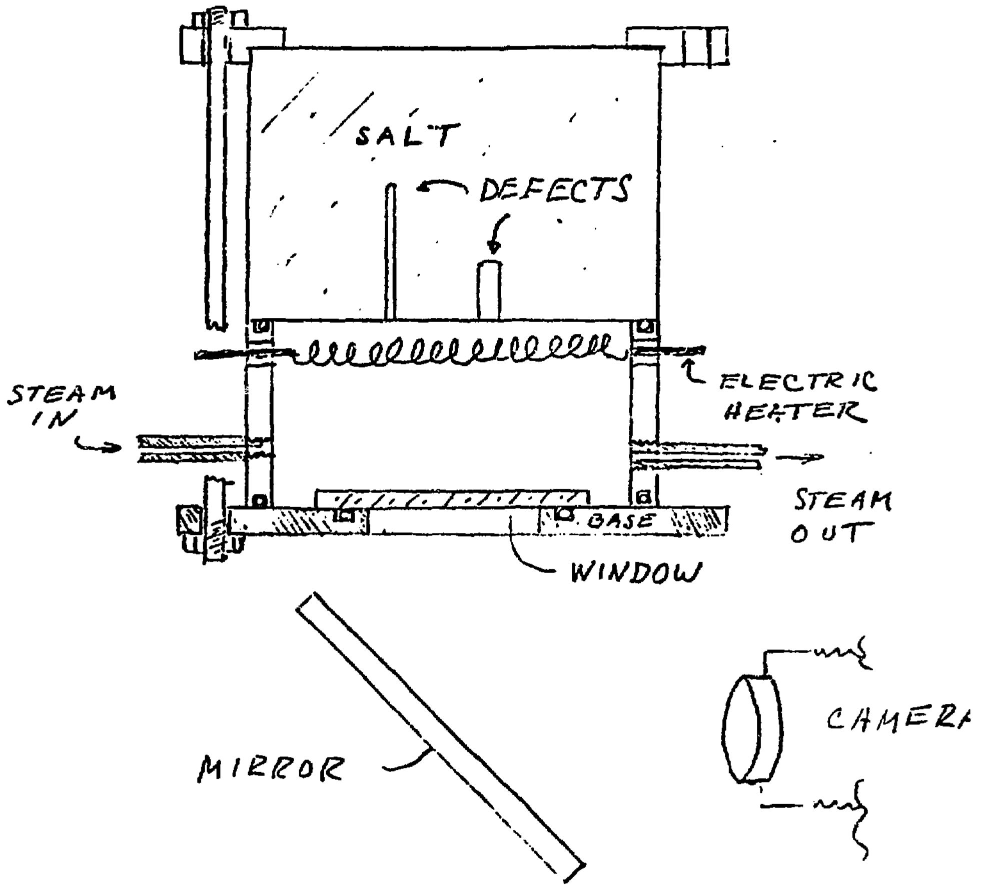
STATUS:

In planning and analysis stage.

REFERENCES:

1. S. Sourirajan and G. C. Kennedy, "The System H_2O-NaCl at Elevated Temperatures and Pressures," American Journal of Science 260, 115-141, February,1960.

2. S. Ridgway, "On the Interaction of Steam with the Cavity Wall," RDA-IR-018-4100, February, 1974.



S. Ridgway March 13

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EXPERIMENT # : 8

NAME : Laboratory Cavity Experiment

PROJECT LEADER:

PURPOSE : The purpose of this experiment is to develop a better insight on the cavity phenomenology and engineering features of the PACER principle employing systems which have been scaled down to laboratory proportions.

TASKS : 2.4, 3.1, 3.2, 5.1.

DESCRIPTION :

Cavities about 3 in. diameter will be produced in blocks of salt 12 to 18 in. diameter. The blocks will be enclosed in a high pressure container capable of applying overburden pressure to the outside of the blocks. Pipes will pass through the container and into the cavity, simulating an actual cavity system.

Means will be provided to heat and pressurize the cavity using steam simulating actual operating conditions. Cavity pressure will be varied to simulate actual pressure variations. Outside temperature of block will be controlled to simulate temperature distribution (or gradient) in actual cavity.

Larger cavities in the range of 12 to 18 in. diameter in blocks of salt about 6 ft diameter will be tested in a larger high pressure container similar to the above tests. Provision will be made for explosive shock-type loading to more closely simulate actual cavity operating conditions.

This equipment will be employed to carry out the following tasks:

1. Verify stress and creep analysis results for cavity in homogeneous salt. Test over a range of cavity temperatures and pressures including simulation of stress distribution and temperature gradients.
2. Observe fatigue characteristics and effect of artificial faults by repeated loading simulating actual operating conditions.
3. Observe results of suddenly applied shock-type loading.
4. Extend tests to non-homogeneous salt samples obtained from salt domes.
5. Verify predictions of pipe and pipe seal performance and observe effects of penetrations on stress, creep and fatigue characteristics of cavity.
6. Study scale effects by comparing difference in performance of 3-in. and 18-in. diameter cavities.
7. Study the simulated behavior of startup and shutdown.
8. Study the dispersion and collection of debris from exploding wires.

This experiment will be preceded by a careful analysis to explore the validity of these seven tasks, to elaborate the details of each task, and to add additional tasks that would seem appropriate.

MILESTONES:

3/74 Experiment rewritten in light of analysis.

Experiments in the small pressure vessel would be executed first. A reasonable time for the complete experiment would be three years.

RESOURCES:

DOS-1	Coordination
M-2	Plan and execute experiment
ENG-6	Consultation
WX-3	Consultation
T-3	Consultation
J-9	Consultation
RDA	Consultation

FACILITIES:

The facilities are available at LASL to execute this experiment. M Division has special expertise in designing, fabricating, and handling the large pressure vessels that will be required. In addition to adequate laboratory space, adequate temperature, pressure, and strain sensing and recording equipment will be required. For the larger experiments of the order of 100 grams of explosive would be detonated. This would require special operating procedures.

STATUS:

This experiment is recognized as an important and complicated one. *Numerous discussions have been held in an attempt to better resolve its* details.

REFERENCES:

EXPERIMENT NO : 9

NAME : Anhydrite Creep Experiments

PROJECT LEADER : LASL, C. A. Anderson/RDA, A. Fields

PURPOSE : The purpose of this experiment is to determine the creep behavior of the material in the anhydrite seams at conditions typical of PACER operating conditions.

TASKS :

DESCRIPTION :

Anhydrite ($CaSO_4$) seams occur in halite domes which have been proposed for use in PACER experiments. The nearly vertical seams are made up of an approximately nine to one mixture of anhydrite and halite and their presence can degrade or enhance cavity stability by weakening or stiffening the deposit against long term and transient creep. For this reason experimental data on the creep properties of anhydrite are needed. Evidence that the presence of anhydrite, even in modest quantities, can affect halite's creep properties is given in (1).

The object of this experiment is to support the PACER stability calculations by providing experimental data on the creep characteristics of the material found in the anhydrite seams of a potential PACER salt dome. Using cylindrical specimens taken from an actual anhydrite seam, differential stress-strain curves will be determined at confining pressures of 2 kilobars, temperatures from 100°C to 500°C, and strain-rates from 10^{-3} to 10^{-8}/sec as described by Heard (2) for Halite. The experiments will be carried out at 2 kilobars in order to compare with Heard's creep data on halite.

If, as anticipated, the creep data for the material of the anhydrite seams is greatly different from that of halite itself, then the long term cavity stability problem will be explored using a halite calculational model with embedded anhydrite seams possessing the experimentally determined creep behavior.

MILESTONES:

Experiments on the creep behavior of the anhydrite material will be run concurrently with the creep rupture experiments on halite. Completion of the project would require about two years concluding with a summary report.

RESOURCES:

DOS-1	Coordination
WX-3	Plan and Execute Experiment
RDA	Consultation

FACILITIES REQUIRED:

Anhydrite samples will be taken from actual anhydrite seams. An MTS system will be used to carry out axial loading tests at constant strain-rates on the samples at confining pressures of 2 kilobars and temperatures of 100°C, 200°C, 300°C, 400°C, and 500°C. The additional equipment provided for the halite rupture experiments would be sufficient for these tests.

REFERENCES:

1. H. Borchert and R. Muir, Salt Deposits, Van Nostrand, London, (1964) Pg. 276-279.
2. H. Heard, Steady-state flow in polycrystalline halite at pressure of 2 kilobars, Geophysical Monograph Series, Vol. 16, American Geophysical Union, Washington (1972) Pg. 191-209.

EXPERIMENT # : 10

NAME : Radiation Deposition in Salt

PROJECT LEADER: RDA, Hubbard/LASL, Nutt

PURPOSE : The deposition of small fractions of the radiation energy from an exploding device in the cavity wall could result in the deterioration of the cavity wall. The purpose of this experiment is to develop a detailed understanding of this deposition and its consequences.

TASKS : 2.1, 2.2, 2.4, 5.1, 8.2

DESCRIPTION : The detailed description of this experiment will be provided at a later date.

MILESTONES :

7/74 Parametric calculations complete
Experiment defined

RESOURCES :

WX-2 Plan and execute experiment
RDA Plan and consult on experiment

FACILITIES REQUIRED:

To be stipulated

REFERENCES:

PACER PROGRAM

PHASE 1 - THEORETICAL AND LABORATORY STUDIES

Part *III*, Phase 1 Cost

This section contains the costs associated with Phase 1 of the PACER program. It should be emphasized that the costs are preliminary.

Definitions

FY	Fiscal year
Org	Organization
GP	Organizational group at LASL
SM	Staff member
GR	Graded series or technicians
S&I	Salary and indirect cost
U.C.	Unusual cost. This includes costs for shop services, computing, and other outside cots.
Equip	Equipment

PACER, PHASE 1, PROJECT 1

Estimated Cost

Task	FY	Org	GP	SM	GR	S&I K$	U.C. K$	Total K$
1.1 Device Definition	74	LASL	DOS-1	0		0		
	T			0.2		4.0		4.0
	74		TD-2	0.2		3.0	4.0	7.0
	T			1.5		50.0	19.0	69.0
	74		TD-4	0				
	T			0.5		17.0	8.0	25.0
	74		ENG		0.1	0.2		0.2
	T				0.1	0.2		0.2
	74		WX-1					
	T			0.25	0.1	10.0		10.0
	74		WX-3					
	T			0.25	0.1	10.0		10.0
	74	RDA		0.05				3.5
	T			0.15				10.5
1.2 Device Cost Estimate	74	LASL	DOS-1	0.1		2.0		2.0
	T			0.5		21.0		21.0
	74	RDA		0				
	T			0.05				3.5
	T	ALO		0				
1.3 Device Safety	74	LASL	DOS-1	0.1		2.0		2.0
	T			0.5		21.0		21.0
	74		WX-1					
	T			0.5		20.0		20.0
	74		WX-3					
	T			0.5		20.0		20.0
	74	Sandia						
	T							
	74	RDA		0				
	T			0.1				7.0
	T	ALO		0				
Totals	74	LASL		0.4	0.1	7.2	4.0	11.2
	T	LASL		4.7	0.3	173.2	27.0	200.2
	74	RDA		0.1				7.0
	T			0.3				21.0
	74	ALO		0				

PROJECT 2, CAVITY PHENOMENOLOGY

Task	FY	Org	GP	Man/yr SM	Man/yr GR	S&I $K	UC $K	Total $K
2.1 Working Fluid	74	LASL	WX-2	0.3		12.5	1.0	13.5
	T			0.5		21.0	2.0	23.0
	74		DOS-1	0.1		5.0		5.0
	T			0.2		11.0		11.0
	74	RDA		0.5				35.0
	T			1.5				105.0
2.2 Nuc. Exp. Invest. (t (t < 1 sec)	74	LASL	DOS-1	0.1		5.0		5.0
	T			0.2		11.0		11.0
	74		J-10	0.2		7.2	4.8	12.0
	T			0.75		27.0	15.0	42.0
	74		T-3	0				
	T			0				
	74		T-4	0.1		1.8	4.2	6.0
	T			0.75		27.0	8	35.0
	74	RDA		0.5	0.5			60.0
	T			1.5	1.5			180.0
2.3 Circ. Working Fluid	74	LASL	T-3	1.0		33.0	13.0	46.0
	T			2.0		67.0	27.0	94.0
	74		DOS-1	0.1		5.0		5.0
	T			0.2		11.0		11.0
	74	RDA		0.05				3.5
	T			0.15				10.5
2.4 Cavity Integrity-Creep Effects	74	LASL	WX-3	0.25		4.5	7.2	11.7
	T			2.0		62.0	24.0	88.0
	74		DOS-1	0.1		5.0		5.0
	T			0.2		11.0		11.0
	74	RDA		0.2				14.0
	T			1.0				70.0
Project 2 Cavity Phenomenology	74	LASL		2.2		79.0	30.2	109.2
	T			6.8		250.0	76.0	326.0
	74	RDA		1.25	0.5			112.0
	T			4.15	1.5			365.5

PROJECT 3

Task	FY	Org	GP	Man/Yr SM	Man/Yr GR	S&I $K	U.C. $K	Total $K
3.1 Trade Studies	74	LASL	DOS-1	0.1	-	5.0	..	5.0
	T			1.0		55.0	2.0	57.0
	74		ENG-6	0.2		6.5	0.4	6.9
	T			6.0	3.0	375.0	50.0	425.0
	74	RDA		0.2				14.0
	T			2.0	0.8			180.0
3.2 Primary	74	LASL	DOS-1					
	T			0.5		27.0	1.0	28.0
	74	ENG-6		0.2		6.5	0.4	6.9
	T			6.0	3.0	375.0	50.0	425.0
	74	RDA		0.2				14.0
	T			2.0	0.8			180.0
3.3 Materials	74	LASL	DOS-1					
	T			0.5		27.0		27.0
	74		ENG-6	0.2		6.5	0.4	6.9
	T			3.0		150.0	25.0	175.0
	74	RDA		0.1				7.0
	T			2.0	0.8			180.0
3.4 Containment	74	LASL	DOS-1					
	T			0.5		27.0	1.0	28.0
	74		ENG-6	0.2		6.5	0.4	6.9
	T			2.0	2.0	150.0	25.0	175.0
	74		J-9					
	T			1.0		50.0	5.0	55.0
	74	RDA		0.1				7.0
	T			2.0	0.8			180.0
3.5 Device Injection	74	LASL	DOS-1					
	T			0.5		27.0	1.0	28.0
	74		ENG-6	0.2		6.5		6.5
	T			6.0	2.0	350.0	50.0	400.0
	74		J-6					
	T			1.0		50.0	5.0	55.0
	74	RDA		0.1				7.0
	T			1.0	0.8			110.0
Project 3 Total	74	LASL		1.1		37.5	1.6	39.1
	T			28.0	10.0	1663.0	215.0	1878.0
	74	RDA		0.7				49
	T			9.0	4.0			830

PROJECT 4, ECONOMICS

Task	FY	Org	GP	Man/yr SM	Man/yr GR	S&I K$	U.C. K$	Total K$
4 Economics	74	LASL	DOS-1	0.1		5.0		5.0
	T			0.3		15.0		15.0
	74	RDA		0.05				3.5
	T			0.3				21.0

PROJECT 5, SAFETY AND ENVIRONMENTAL CONSIDERATIONS

Task	FY	Org	GP	Man/yr SM	Man/yr Gr	S&I K$	U.C. K$	Total K$
5.1 Safety	74	LASL	DOS-1					
	T			0.5		27.0		27.0
	74		H-1					
	T			0.5		20.0	5.0	25.0
	74		H-3					
	T			0.5		20.0		20.0
	74		ENG-6					
	T			1.0		40.0		40.0
	74	RDA		0.25				17.5
	T			1.50				105.0
5.2 Seismic	74	LASL	DOS-1	0.1		5.0		5.0
	T			0.2		11.0		11.0
	74		J-9					
	T			1.0		50.0	10.0	60.0
	74	RDA		0.15				10.5
	T			0.3				21.0
5.3 Legal	74	LASL	DOS-1					
	T			0.25		13.5		13.5
	74	RDA						
	T			0.05				3.5
5.4 P.R.	74	LASL	DOS-1					
	T			0.25		13.5		13.5
	74	RDA						
	T			0.25				17.5
Project 5 Total	74	LASL		0.1		5.0		5.0
	T			4.2		195.0	15.0	210.0
	74	RDA		0.4				28.0
	T			2.1				147.0

PROJECT 6, FUEL RECOVERY AND PROCESSING

Task	FY	Org	GP	Man/yr SM	Man/yr GR	S&I $K	UC $K	Total $K
6.1 Chemical and Physical State	74	LASL	DOS-1					
	T			0.2		11.0		11.0
	74		WX-2					
	T			0.5		27.0		27.0
	74	RDA		0.1				7.0
	T			2.1	1.0			197.0
6.2 Solids Recovery	74	LASL	DOS-1					
	T			0.2		11.0		11.0
	74		WX-2					
	T			0.5		27.0		27.0
	74		CMB-11					
	T			1.0		45.0		45.0
	74		H-7					
	T			0.1		4.0		4.0
	74	RDA						
	T			1.0				70.0
6.3 Production & Separation of ^{233}U	74	LASL	DOS-1					
	T			0.5		27.0		27.0
	74		WX-2					
	T			1.0		42.0		42.0
	74		TD-1					
	T			1.0		42.0	15	57.0
	74		TD-3					
	T			1.0		42.0	15	57.0
	74		CMB-11					
	T			2.0		90.0	10	100.0
	74	RDA						
	T			2.0				140.0
6.4 Production & Separation of ^{239}Pu	74	LASL	DOS-1					
	T			0.5		27.0		27.0
	74		WX-2					
	T			1.0		42.0		42.0
	74		TD-1					
	T			1.0		42.0	15	57.0
	74		TD-3					
	T			1.0		42.0	15	57.0
	74		CMB-11					
	T			2.0		90.0	10	100.0
	74	RDA						
	T			2.0				140.0
Project 6 TOTALS	74	LASL						
	T			13.5		611	80	691.0
	74	RDA		0.1				7
	T			7.1	1.0			547.0

PROJECT 7, GEOLOGY, SITE DEFINITION AND SELECTION AND CAVITY CONSTRUCTION

Task	FY	Org	GP	Man/Yr SM	Man/yr GR	S&I $K	UC $K	Total $K
Project 7 Totals	74	LASL		0.2		6.7	1.2	7.9
	T			4.8	2.0	293.9	26.0	319.0
	74	RDA		0.15				10.5
	T			2.3				161.0

PROJECT 8 FEASIBILITY STUDY FOR NUCLEAR TEST AND EFFECTS FACILITY*

Task	Org	GP	Man yr SM	Man yr GR	S&I $K	UC $K	Total $K
8.1 Planning and Coordination	LASL	DOS-1	0.4		22.0		22.0
		J-DO	0.5		27.0		27.0
		J-6	0.2		10.0		10.0
	RDA		0.5				35.0
8.2 Cavity Phenomenology	LASL	DOS-1	0.1		5.5		5.5
		J-6	0.1		5.0	1.0	6.0
		J-7	0.2		10.0	1.5	11.5
		J-8	0.2		10.0	1.5	11.5
		J-9	1.0		50.0	20.0	70.0
		J-10	0.3		15.0	6.0	21.0
		J-15	0.2		10.0	4.0	14.0
		T-3	0.2		10.0	4.0	14.0
		T-4	0.2		10.0	4.0	14.0
		WX-2	0.2		10.0	1.0	11.0
		WX-3	0.3		15.0	7.0	22.0
	RDA		1.0				70.0
8.3 Engineering	LASL	DOS-1	0.1		5.5		5.5
		J-6	0.8		40.0	6.0	46.0
		J-7	0.6	0.5	43.0	4.0	47.0
		J-8	0.4		20.0	3.0	23.0
		J-9	0.1		5.0	2.0	7.0
		J-12	0.1		5.0	2.0	7.0
		J-14	0.1		5.0	1.0	6.0
		J-16	0.5		25.0	4.0	29.0
		CNC-11	0.1		5.0	1.0	6.0
	RDA		1.0				70.0
8.4 Diagnostics	LASL	DOS-1	0.1		5.5		5.5
		J-8	0.2		10.0	1.5	11.5
		J-9	0.2		10.0	4.0	14.0
		J-10	0.2		10.0	4.0	14.0
		J-12	0.3		15.0	6.0	21.0
		J-14	0.5		25.0	4.0	29.0
		J-15	0.1		5.0	2.0	7.0
		J-16	0.3		15.0	2.0	17.0
		CNC-11	0.3		15.0	3.0	18.0
	RDA		1.0				70.0

Project 8 cont.

Task	Org	GP	Man yr SM	Man yr GR	S&I $K	UC $K	Total $K
8.5 Safety and Environmental (including containment)	LASL	DOS-1	0.1		5.5		5.5
		J-1	0.1		5.0	1.0	6.0
		J-6	0.2		10.0	1.5	11.5
		J-7	0.2		10.0	1.5	11.5
		J-8	0.2		10.0	1.5	11.5
		J-9	0.5		25.0	10.0	35.0
		J-10	0.1		5.0	2.0	7.0
		J-12	0.1		5.0	2.0	7.0
		J-14	0.1		5.0	1.0	6.0
		J-15	0.5		25.0	10.0	35.0
		J-16	0.1		5.0	1.0	6.0
		CNC-11	0.1		5.0	1.0	6.0
		H-1	0.4		20.0	4.0	24.0
	RDA		0.5				35.0
8.6 Site Definition, Selection and Cavity Construction	LASL	DOS-1	0.1		5.5	1.0	6.5
		J-6	0.1		5.0	1.0	6.0
		J-9	0.1		5.0	1.0	6.0
	RDA		0.5				35.0
8.7 Cost	LASL	DOS-1	0.1		5.5		5.5
		J-6	0.1		5.0		5.0
		J-7	0.2		10.0		10.0
		J-8	0.1		5.0		5.0
		J-9	0.1		5.0		5.0
		J-12	0.1		5.0		5.0
		J-14	0.1		5.0		5.0
		J-15	0.1		5.0		5.0
		J-16	0.1		5.0		5.0
		H-1	0.1		5.0		5.0
	RDA		0.2				14.0
Project 8 Totals	LASL		13.2	0.5	680.0	139.0	819.0
	RDA		4.7				329.0

*Costs estimated on the basis of the following predications:

- Minimal code, experimental and theoretical development over and beyond that required for PACER.
- Improvement in project definition contingent upon the further funding and/or PACER progress.

PROJECT 9, SYSTEM ANALYSIS, COORDINATION AND PLANNING

Task	FY	Org	GP	Man/yr SM	Man/yr GR	S&I $K	U.S. $K	Total $K
Project Totals	74	LASL	DOS-1	0.2		10.0		10.0
	T			2.0		110.0	10.0	120.0
	74	RDA		0.5				35.0
	T			3.0				210.0

PROJECT SUMMARY

Project	FY	Org	Man/yr SM	Man/yr GR	S&I $K	U.C. $K	Total $K
1. Thermo. Device	74	LASL	0.4	0.1	7.2	4.0	11.2
	T		4.7	0.3	173.2	27.0	200.0
	74	RDA	0.1				7.0
	T		0.3				21.0
2. Cavity Phenom.	74	LASL	2.2		79.0	30.2	109.2
	T		6.8		250.0	76.0	326.0
	74	RDA	1.25	0.05			112.0
	T		4.15	1.50			365.5
3. Engineering	74	LASL	1.1		37.5	1.6	39.1
	T		28.0	10.0	1663.0	215.0	1878.0
	74	RDA	0.7				49.0
	T		9.0	4.0			830.0
4. Economics	74	LASL	0.1		5.0		5.0
	T		0.3		15.0		15.0
	74	RDA	0.05				3.5
	T		0.3				21.0
5. Safety & Environ. Considerations	74	LASL	0.1		5.0		5.0
	T		4.2		195.0	15.0	210.0
	74	RDA	0.4				28.0
	T		2.1				147.0
6. Fuel Recovery	74	LASL					
	T		13.5		611.0	80.0	691.0
	74	RDA	0.1				7.0
	T		7.1	1.0			547.0
7. Geology, Site Definition & Cavity Constr.	74	LASL	0.2		6.7	1.2	7.9
	T		4.8	2.0	293.0	26.0	319.0
	74	RDA	0.15				10.5
	T		2.3				161.0
8. Nuclear Test & Effects Facility	74	LASL					
	T		13.2	0.5	680.0	139.0	819.0
	74	RDA					
	T		4.7				329.0

Project Summary, Continued

Project	FY	Org	Man/yr SM	Man/yr GR	S&I $K	U.C. $K	Total $K
9. System Analysis Coordination & Planning	74	LASL	0.2		10.0		10.0
	T		2.0		110.0	10.0	120.0
	74	RDA	0.5				35.0
	T		3.0				210.0
Project Totals*	74	LASL	4.2	0.1	150.4	37.0	187.4
	T		77.5	12.8	3990.0	588.0	4578.0
	74	RDA	3.25	0.05			252.0
	T		33.0	6.5			2632.0

*These totals include the estimated budget for Project 8.

PACER

Experiment #1

Material Studies

FY	Org	GP	SM	GR	S&I K$	U.C. K$	Equip K$	Total K$
74	LASL	WX-2	0.7		32.0	2.0		34.0
T			3.0	2	160.0	40.0	3.0	203.0
74	RDA		0.1					7.0
T			0.2					14.0

PACER

Experiment #2

Halite Creep Rupture

FY	Org	GP	SM	GR	S&I K$	U.C. K$	Equip K$	Total K$
74	LASL	WX-3						
T			0.25	1.0	40.0	10.0	20.0	70.0
74	RDA							
T			0.1					7.0

PACER

Experiment #3

Primary Loop Mockup

FY	Org	GP	SM	GR	S&I K$	U.C. K$	Equip K$	Total K$
74	LASL	ENG-6						
T			6	7	380.0	370.0	150.0	900.0
74	RDA		0.05					3.5
T			0.25					17.5

PACER

Experiment #4

Shaft Sealing

FY	Org	GP	SM	GR	S&I K$	UC K$	Equip K$	Total K$
74	LASL	ENG-6						
T			5.0	4.0	350.0	200.0	125.0	675.0
74	RDA							
T			0.75					52.5

PACER

Experiment #5

Device Injection

FY	Org	GP	SM	GR	S&I K$	U.C. K$	Equip K$	Total K$
74	LASL	ENG-6						
T			5.0	5.0	300	200	125	625
74	RDA							
T			0.75					52.5

PACER

Experiment #6

Dynamic Loading

FY	Org	GP	SM	GR	S&I K$	U.C. K$	Equip K$	Total K$
74	LASL							
T		M-4	5.0	5.0	300	200	150	650.0
74	RDA							
T			0.75					52.5

PACER

EXPERIMENT # 7

Steam-Cavity Wall Interaction Experiments

FY	Org	GP	SM	GR	S&I K$	U.C. K$	Equip. K$	Total K$
74	LASL	WX-2						
T			0.5		24	20		44
74	RDA							
T			0.15	0.5				37

PACER

Experiment # 8

Laboratory Cavity Simulation

FY	Org	GP	SM	GR	S&I K$	U.C. K$	Equip K$	Total K$
74	LASL	ENG-6						
T			4	2	200	450	150.0	800.0
74	RDA		0.1					7.0
T			0.5					35.0

PACER

Experiment #9

Anhydrite Creep Rupture

FY	Org	GP	SM	GR	S&I K$	U.C. K$	Equip K$	Total K$
74	LASL	WX-3						
T			0.25	1.0	40.0	10.0	20.0	70.0
74			0.1					7.0

PACER

Experiment #10
Radiation Deposition in Salt

FY	Org	GP	Man yr SM	Man yr GR	S&I $K	UC $K	Equip $K	Total $K
74	LASL	WX-2						
T			0.50	1.0	50.0	43.0		93.0
74	RDA		0.10					7.0

PHASE I Summary

	FY	Org	Man yr SM	Man yr GR	S&I $K	UC $K	Total $K
Projects	T	LASL	77.5	12.8	3990	588	4578
Experiments	T	LASL	29.5	28.0	1844	1543	3387
Total LASL	T	LASL	107.0	40.8	5834	2131	7975
Projects	T	RDA	33.0	6.5			2632
Experiments	T	RDA	3.65	0.5			282
Total RDA	T	RDA	36.65	7.0			2914
TOTAL LASL & RDA	T		143.65	47.8			10,889
Equipment (LASL)							743

Ref. 3

RDA-TR-4100-003

PROJECT PACER FINAL REPORT

JULY 1974

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PREFACE

PACER is a concept which utilizes known technology to achieve electric power from fusion explosions. The explosions are used to heat steam contained in a large underground cavern, and the heated steam subsequently drives a conventional power plant.

The importance of the PACER concept was recognized by scientists at R & D Associates (RDA) who also became convinced of its practicality through their familiarity with feasibility studies of the construction of large cavities for siesmic decoupling of nuclear tests [1,2]. In October 1972, RDA proposed development of the PACER concept [3] and was joined by the Los Alamos Scientific Laboratory (LASL) in this effort. In July 1973, the AEC funded a one-year study program to LASL and RDA jointly. This study primarily addresses questions of safety and feasibility of containing the repeated explosions in underground cavities.

The report begins with a summary of the present status and recommendations for future work. The text of the report is divided into sections corresponding to the project heading chosen for the PACER program, with each of these sections containing a descriptive summary report of work done on that particular project. A separate volume of appendixes, similarly divided, contains detailed reports of work.

ACKNOWLEDGMENTS

Many RDA staff members and consultants have contributed to the first year of work on PACER. Written contributions which have not otherwise received formal publication are included in the Appendixes to this report. In addition, it is a pleasure to acknowledge the major contributions made by D. T. Griggs, R. P. Hammond, A. L. Latter and E. A. Martinelli, which cover all aspects of the work.

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SUMMARY AND RECOMMENDATIONS

The major results of the first year of the work are:

- The effect of explosions on the cavity walls seems manageable. Fireball mixing probably occurs quickly preventing convective heating. Radiant heating can be controlled by adding a small amount of NO_2 to any fluid. No adverse chemical effects from either H_2O or CO_2, the two candidate fluids, have been discovered at operating conditions.

- Conceptual design of the primary loop and heat exchangers has been engineered in enough detail to make economic feasibility plausible. Experiments have been laid out to help choose materials and design seals. The level of technology involved is that applicable to a pressurized water reactor.

- A thermo-physical mechanism of producing crack growth has been proposed and an experiment designed to test it, although it requires a pre-existing crack that does not seem compatible with cavity operating conditions. The growth could not occur with CO_2 as a working fluid. No classical crack growth can occur since no tensile stresses develop.

- The very low fission waste in the cavity, due to the use of fusion energy, can probably be further reduced by filtering the fluid to approximately a tenth of a percent of the fission product inventory of a standard power reactor.

- Economic comparisons appear to be favorable to PACER, especially if breeding and recovery of ^{233}U or Pu proves feasible as conceptualized.

- The operation of PACER in a primarily production mode has been suggested, since a 2 GW(e) PACER can supply fuel for eight 1 GW(e) reactors. Thorium would be the fertile material, and the ^{233}U produced would be diluted with natural U before shipment to reactors, eliminating it as a target for thieves.

A sketch of the conceptualized facility is shown in Figure 1.

The major technical question of cavity integrity under repeated explosive loading cannot be solved on paper, and awaits experiments. An orderly approach to this development was made in the first RDA Proposal 72-26 [3], and during the past year the details have been greatly elaborated. Since everything that has been learned during the first year of study tends to increase the potential inherent in the PACER idea, and since no serious problems have been discovered, we believe that crucial experimental programs should be funded immediately, according to the schedule given in Figure 2 [4].

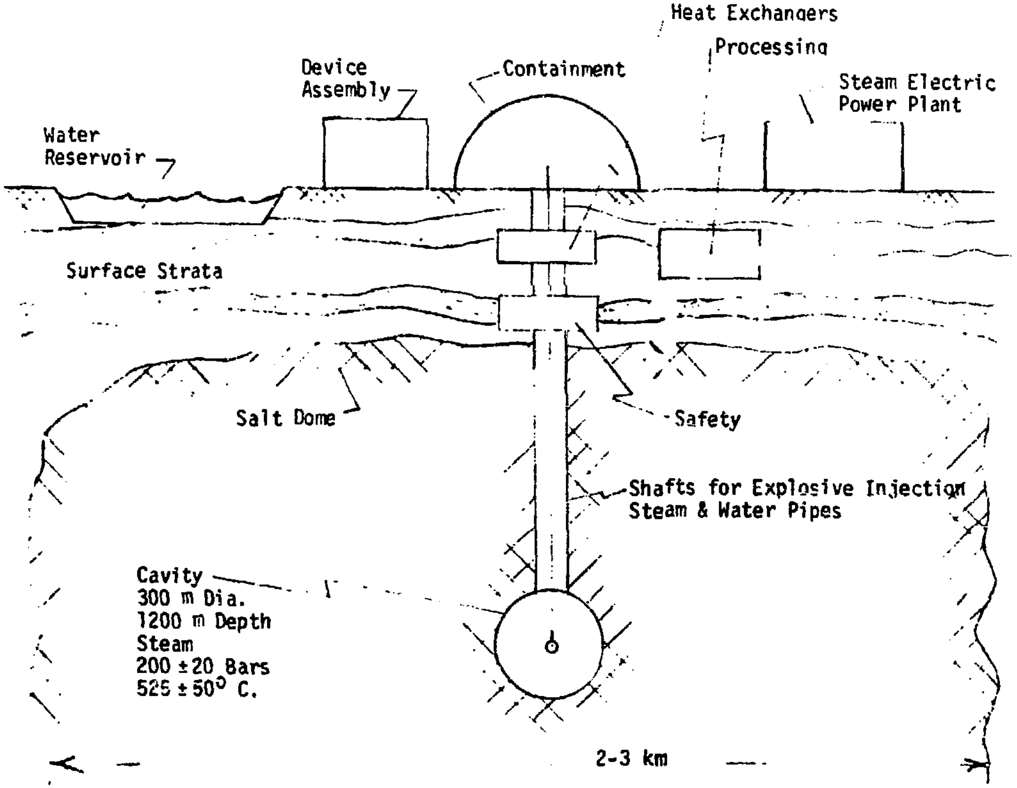

Figure 1. Concept -- 2000 MW Power Plant

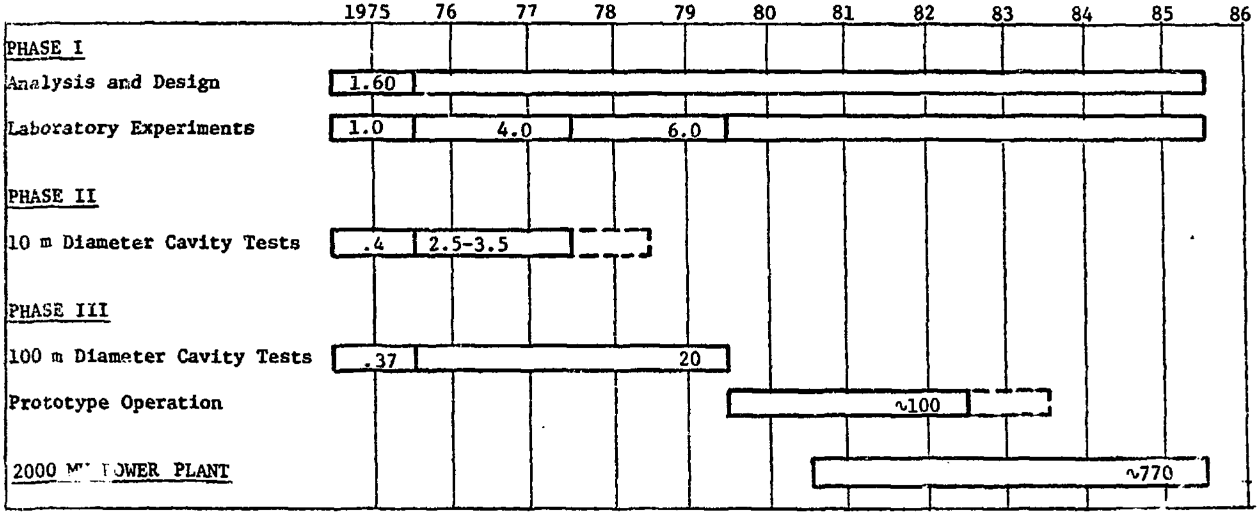

Figure 2. Program Schedule and Costs ($M)

2

PROJECT 1. THERMONUCLEAR DEVICE DEVELOPMENT

The purpose of Project 1 is the development of suitable fusion explosives for PACER application.

RESEARCH RESULTS

RDA's role has been that of consultant. Inputs to establishment of device criteria were incorporated into DOS-1-74, PACER Thermonuclear Explosives Constraints [5]. In addition, preliminary discussions have been held on safety, security and economic issues relevant to the device design and production.

PROJECT 2. CAVITY PHENOMENOLOGY

The purpose of Project 2 is to determine the immediate and long-term explosion effects on the cavity with the object of choosing optimal materials and parameters for designing a PACER facility.

RESEARCH RESULTS

Working Fluid

The use of steam as a working fluid is the first choice for the following reasons:

1. It is condensible, making possible shutdown without venting all the fluid, a quenching system for safety release in event of leak, and low-pumping power and hence reasonable thermal efficiency.

2. It is available, economical, and no new engineering practice is needed.

3. As far as is known, it is chemically compatible with the salt walls and properly-chosen steel pipes. (Experiments have been designed to test this point [6].)

A second choice, as a backup, is CO_2. Although not condensible, it is nearly so and therefore provides good thermal efficiency. It is chemically less reactive than H_2O.

Both H_2O and CO_2 require the addition of a few percent NO_2 to provide sufficient opacity in the visible and infrared to shield the walls from fireball radiation.

Other fluids which were considered and discarded were:

- nitrogen and argon -- too expensive
- hydrogen -- many engineering problems, too expensive, and the assumed advantage of shock reduction was found not to be true
- air -- economical, but reactive and poor thermal efficiency.

All the gases, excluding CO_2 which is nearly condensible, require a great deal of extra piping as compared to H_2O and would probably be ruled out on that account alone. This point is discussed further under Project 3--Engineering.

Nuclear Explosion ($t<1$ sec)

A radiation-hydrodynamic computer code (Harold) was used to calculate shock effects from an explosion in the center of an H_2O-filled cavity. Since data on opacity of H_2O were not yet available and since radiation flow is not a dominant effect, it was decided to use the opacity of air for the fluid as an input parameter in the code. The results of this calculation, described in Appendix A, showed that the shock overpressure after reflection at the cavity wall (radius 200 m, yield 100 kT) was about 200 bars, and the pulse had a half-width of $\sim$50 msec. This is a lower pressure and longer time than the scaling prediction in RDA Proposal 72-26 [3].

After reflection at the spherical wall, the shock converges on and recompresses the fireball, which has expanded very little. During this recompression, the higher density steam surrounding the low-density fireball is decelerated so that the boundary separating the two regions is Taylor unstable and mixing occurs. Estimates (shown in Appendix A) indicate that disturbances of ∿10 meters or less are highly unstable and mix rapidly. Since the shock reverberation time is ∿1/2 sec, the mixing may be repeated several times before the fireball rises very far.

Long-Term Heating

The heating effect of the thermal pulse from the fireball on the salt wall of the cavity is critically dependent upon the amount of impurities in the salt, which determines how far the radiation penetrates. This distance will in turn determine how much NO_2 or air must be added to the steam to prevent melting appreciable salt. Since further optical experiments are needed to determine the actual deposition length of fireball radiation in salt dome material, this length was made a variable parameter in a set of calculations modeling the deposition and subsequent diffusion of heat in the cavity walls. The results, given in Appendix A, indicate that very clear salt presents no problem; but if the deposition length is less than a meter, the gas opacity must be chosen to minimize the effect.

PROJECT 3. ENGINEERING

The purpose of this project is the development of a complete conceptual engineering design for a PACER facility, with primary consideration given to safety and cost.

RESEARCH RESULTS

Primary Loop

Engineering studies, concerned primarily with the feasibility of generating electrical power, were begun using the following operating conditions specified in the original proposal [3].

Cavity working fluid pressure	440 bars
Cavity working fluid temperature	500-600°C
Cavity depth	2 km
Power output	2000 MW(e)

Preliminary examination indicated that the level of radioactivity in the cavity working fluid would probably make it unwise to use the fluid directly in the power producing turbines. Also it was evident that the pressure was much higher than desirable for turbines and that heat exchanger steam generators operating at 400 bars pressure were undesirable. Another problem was the high cost of the 2 km high-pressure, high-temperature pipes.

A solution to these problems is proposed and analyzed in the section of Appendix B entitled "Throttled Steam for Power Generation." It was concluded that if a two-phase steam (vapor-liquid) system was used, it could be operated with steam pressure in the upcoming pipe reduced to about 170 bars at the surface. This pressure would be satisfactory for the design of heat exchangers and steam generators. The drop in pressure from 440 bars to 170 bars could be used to overcome friction in the upcoming pipes and would result in a significant savings in the cost of the pipes. Further, the working fluid could be returned to the cavity as a liquid resulting in very little pumping power being required to replace the throttling pressure drop from 440 to 170 bars.

It was concluded that a single pipe less than 3 ft inside diameter would suffice and that the pumping power would be less than 100 MW. The thermal efficiency of the cycle, using equipment similar to that developed for pressurized water reactor systems, would be in the 30 to 33 percent range.

For completeness, the possibilities of a gas turbine or Brayton cycle using a gas as the working fluid were investigated (see Appendix Section B.2) Even with no pressure loss due to pipe friction and heat exchanger losses, it was concluded that the 500-600°C temperature limit was too low for good gas turbine performance. The best cycle efficiency obtainable would be less than 17 percent.

Studies of the possibilities of single phase or gas systems are continued in "Pipe Sizes and Pumping Power," Appendix Section B.3. Generally, it was concluded that unreasonably large pipes would be required if the pumping power used to circulate the gas from and to the cavity was to be a small fraction of the terminal power output. The following are typical results for air as the working fluid:

Pump power, MW (200 MW(e) output)	45	135	450
Pipe diameter, ft	11	9	7

Cost estimates for pipes of this diameter and 2 km long indicated the pipe cost would probably exceed the cost of all other items in the power plant.

Continued emphasis of the necessity for using a two-phase H_2O system suggested a review of the NaCl-H_2O equilibrium conditions as described in the Souririjan and Kennedy paper [7]. It was concluded that for NaCl-H_2O vapor equilibrium (no liquid) the cavity pressure should be lowered from 440 bars to 320 bars if the average temperature in the cavity was to be about 550°C. Cavity depth was reduced to 1.45 km.

Previous estimates regarding feasibility were revised to include these new conditions in "Preliminary Estimate of Size, Weight and Cost of Primary Loop High Pressure Pipes," Appendix Section B.4. Results are shown in the following table, assuming the pipes are similar to stainless steel in quality and cost.

	Single Phase All Steam	Two Phase Pressurized Water
Maximum wall thickness, cm	5.0	5.0
Pipe inside diameter, cm	19.5	19.5
Number of pipes	129	36
Pump power, kW	115×10^3	24×10^3
Total weight of pipes, kg	120×10^6	35×10^6
Total cost of pipes at $15/kg	$1800 x 10^6	$525 x 10^6

It was concluded that since the cost of a 2000-MW(e) plant would be about $1400 x 10^6 ($700/kW) excluding the cost of the pipes, the cost of pipes for a single-phase system was high enough to rule out use of such a system. The cost of pipes for the two-phase pressurized water system, though relatively high, was not prohibitive.

The cost of heat exchangers was evaluated in Appendix Sections B.5 and B.6. It was concluded that heat exchanger steam generators would cost about \$30 per kW(e) and that this cost was not a big item in total plant cost.

The thermal conversion efficiency for the pressurized water steam generator systems is generally in the 30 to 33 percent range. This is somewhat disappointing in view of the peak cavity temperature of about 550°C. Various aspects of the factors which contribute to the determination of the thermal conversion efficiency are analyzed in Appendix Section B.7. It was concluded that 30-percent thermal conversion efficiency is about all that can be expected from the pressurized water system and that direct expansion of the cavity steam in the turbines will be necessary if the thermal efficiency of the cycle is to be improved significantly, perhaps to 38 percent. But the problems of corrosion, salt deposition, radioactivity and contamination indicate that further study is required before one can assume that such a direct system is feasible.

The continuing problem of relatively high pipe costs is again studied in "Variation of PACER High Pressure Pipes with Cavity Pressure," Appendix Section B.8. It is evident that lower cavity pressure and associated reduction of pipe length should reduce the cost significantly. Results are shown in the following table for cavity maximum pressure equal to 75 percent of the overburden pressure.

Cavity steam pressure				
maximum, bars	408	312	240	192
minimum, bars	340	260	200	160
Pressurized water pressure, bars	170	130	100	80
Pipe inside diameter, cm	14	20	29	38
Depth, km	2.48	1.89	1.45	1.16
Number of pipes	155	52	22	9.3
Mass of pipes, kg	96×10^6	34×10^6	14×10^6	6.3×10^6
Cost at \$15/kg	1440×10^6	510×10^6	210×10^6	95×10^6

It was concluded that the average cavity operating pressure should be reduced to about 200 bars and that the pipe cost could be reduced to about $\$150 \times 10^6$ or about \$75 per kW(e).

Other Engineering Considerations

Questions about the possible interaction of steam with the cavity wall are discussed in Appendix Section C.3. Air is again examined as a possible working fluid, and in Appendix Section B.10 the costs of the pipes are again evaluated. It was concluded that the cost of the pipes using air as the working fluid is unacceptably high. CO_2 is studied as a working fluid in Appendix Sections A.10 and B.12. Its principal advantage over air is that it can possibly be returned at a temperature near its critical temperature and thus reduce considerably the gas pumping power required and/or the cost of the pipes.

Reduction of the depth to slightly more than 1 km and realization that most available salt domes do not extend upward to the earth's surface made it necessary to consider reducing the cavity diameter from the 400 m originally proposed. Increasing the operating pressure range to ± 20 percent of the average pressure from the proposed ± 10 percent and decreasing the yield per explosion from 100 to 50 kT would reduce the cavity diameter to about 250 m.

The explosions in the cavity produce pressure pulses which may be transmitted upward in the fluid in the pipes. This type of loading was studied in "Attenuation of Weak Shock Waves in Pipes," Appendix Section B.9. It was concluded that there is a problem associated with the pressure pulses and that means for attenuation must be provided in the design of the pipes.

"PACER-Preliminary Engineering Criteria," Appendix Section B.11 addresses the current status and feasibility of various engineering aspects of the PACER project. The general conclusion is that there are feasible solutions to the various engineering problems which have been investigated.

The estimated costs of various major items contributing to the capital cost of a 2000-MW(e) power plant are shown in the following calculations. Total plant cost would probable escalate to around $\$900 \times 10^6$ by the year 1980.

Capital Cost* 2000-MW Power Plant

200 ± 20 Bars 525 ± 50°C 1.2 km Depth	300-m Diameter Unlined Cavity Solution-Salt Dome
	Cost (Million Dollars)
Site selection and testing	10
Cavity and shaft formation	100
Pipes	150
Insertion system	25
Containment system	75
Waste treatment system	15
Site preparation, roads, buildings	25
Heat exchangers	50
Pumps	10
Turbine generators	100
Condensers	20
Piping, auxiliaries, controls	60
Cooling towers	50
Shock isolation	20
Safety, security	10
Engineering, management	50
	770
	385 $/kW(e)

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*1973-74 dollars.

PROJECT 4. ECONOMICS

The purpose of this project is to ensure the economic feasibility of the proposed PACER systems and to estimate PACER's relative competitive position in the energy and fissile material production areas.

RESEARCH RESULTS

Major Cost Elements

An effort has been made to keep cost estimates current for the major system components, viz., for the pipes and heat exchangers, cavity construction, turbine-generators, etc. The way in which these estimates scale with important system parameters has been a major influence in choosing cavity operating conditions, particularly the cost of piping which increases with the 3.5 power of the cavity pressure. This is discussed further under Project 9.

Cost Comparisons

Comparisons of PACER have been made with other electrical energy systems. Results are shown in Figure 3. The data for these comparisons have been collected at Oak Ridge [8] and used in the CONCEPT code. The competitive standing of PACER without breeding depends on the cost of the fuel charge whereas PACER with breeding has a clear advantage over other systems. The effect of varying the cost of the fuel charge is shown in Figure 4.

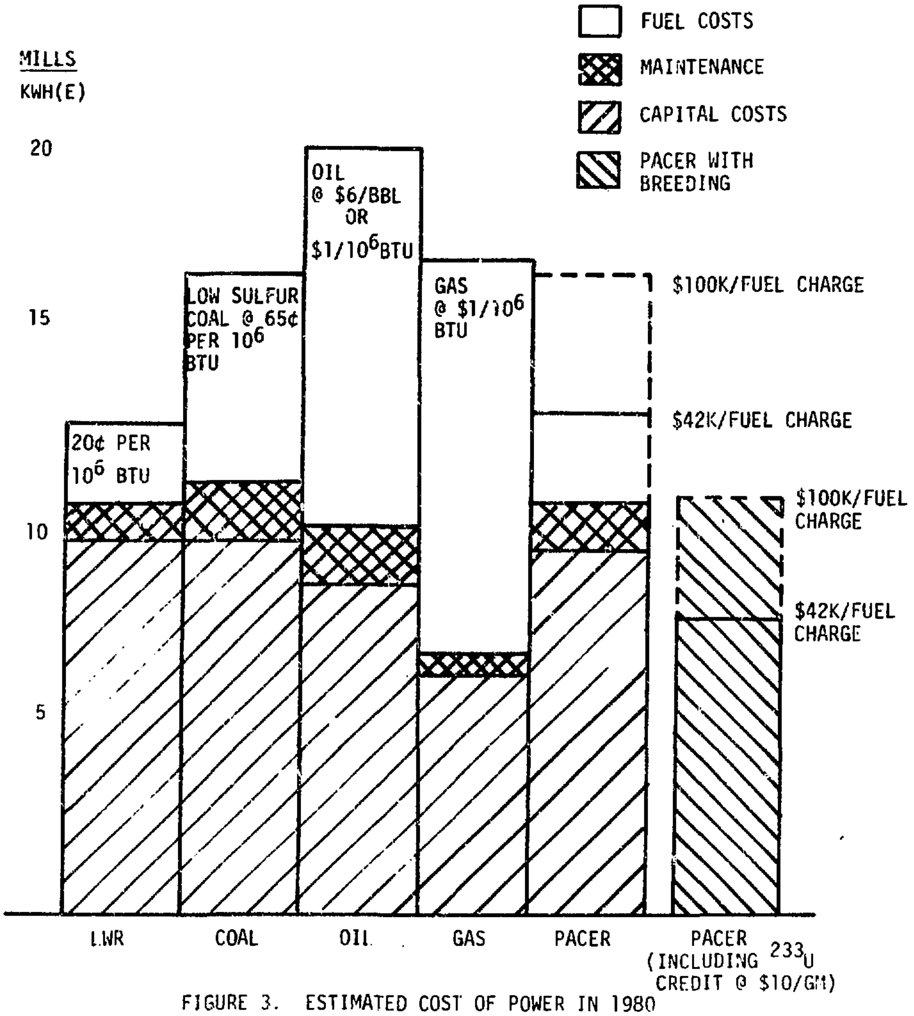

FIGURE 3. ESTIMATED COST OF POWER IN 1980
(80% CAPACITY FACTOR, FIXED CHARGES 15%/YEAR)

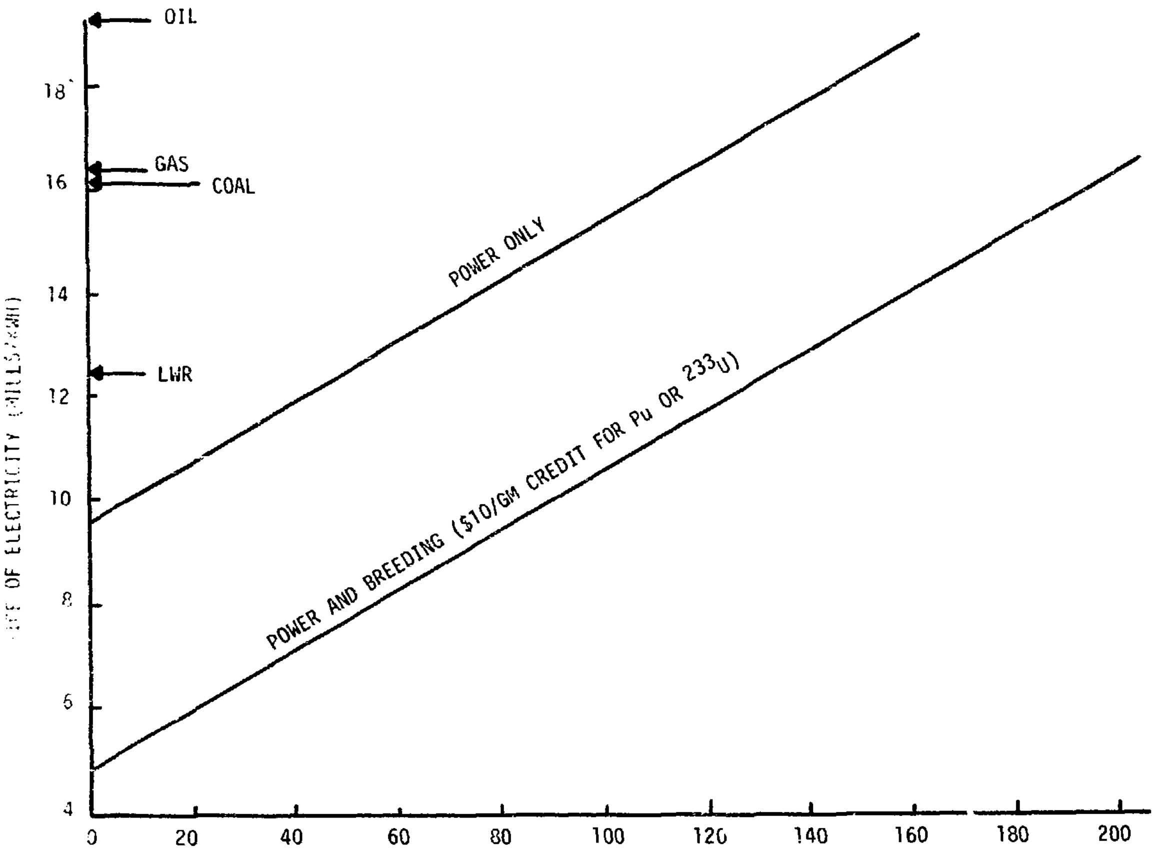

FIGURE 4. COST OF FUEL CHARGE ($\$10^3$)
ESTIMATED 1980 COST OF ELECTRICITY FROM PACER

PROJECT 5. SAFETY, ENVIRONMENTAL AND SECURITY CONSIDERATIONS

The purpose of Project 5 is to ensure that the design of every aspect of PACER will provide safety during many years of operation, to assess the impact of the system on the environment, and to analyze the safeguards required for security against nuclear theft.

RESEARCH RESULTS

Cavity Integrity

The basic integrity of the cavity is provided by the primary design principle: no tensile stresses will be allowed to develop in the geological material. Cracking, in the usual sense, cannot occur in the absence of tensions; nevertheless, an effort was made to discover other sources of cavity failure. One proposal was that NaOH and HCl would be found in quantity in a salt cavity, with resultant chemical deterioration and sloughing of the wall. Fortunately, there is experimental proof that this does not happen, at least in laboratory samples [7,9].

A thermophysical mechanism for crack propagation in salt has been proposed for investigation. (This is planned as Experiment No. 7.) If, by some unexplained mechanism, a long crack should form which protrudes from the cavity, through the heated layer of salt and into the surrounding cold salt, then it is possible under favorable circumstances for the crack to propagate via dissolution of the salt. This is described in detail in Appendix C, but it should be pointed out that a crack in the heated plastic region will close unless the steam pressure is greater than the overburden. It is planned to investigate the crack closure theoretically via computer codes.

Radioactivity

The main sources of radioactivity in a PACER cavity are fission products and tritium. Since the nuclear fuel derives most of its energy from burning deuterium, the initial input of fission products might be a few percent of that from a fission reactor of comparable power level. It is planned to filter the working fluid continuously to remove fission products and other debris material so that no long-lived activities can build up in the fluid. Although detailed studies have not yet been made, this approach appears feasible at modest cost and will probably reduce the concentration of fission products to roughly 1 curie per ton of steam, or $\sim 10^{-3}$ μCi/ml at atmospheric pressure. The inventory of fission products in a PACER cavity will probably be less than a tenth of a percent of the inventory in a conventional power reactor operated at the same power level.

A 2000-MW(e) plant will produce roughly 100 gm of tritium per day. In a steam-filled cavity it will build up (half life is 12 years) to a concentration of $\sim 1/3$ μCi/ml (at atmospheric pressure) after 3 or 4 years of operation. Tritium emits a very low energy electron and is not a particularly hazardous material; in addition, it will be bound to the water as HTO and so cannot leak out as a gas.

Environmental

Above ground, an emergency containment and quenching arrangement will be designed, including a small lake containing enough water to combine with and quench any escaping steam in the event of a leak. Similar systems have been designed already for light water reactors.

Seismic effects are small. Preliminary results indicate displacements of a few centimeters at the cavity wall, corresponding to a few millimeters at the surface above the cavity. At a distance of a few miles from the site, the magnitude of the seismic effect would be acceptable.

Security

- Normal security must, of course, be provided for enriched fissile materials at the site. To make the facility more secure and economical, a completely enclosed power complex is favored. Within the complex, recovered materials would be processed and new parts fabricated so that no highly enriched material ever leaves the complex.

If the facility is being used as a fissile material breeder, the production of ^{233}U is highly favored over ^{239}Pu for security reasons. During fabrication of fuel elements for use by fission reactors, the ^{233}U will be mixed with natural U to an enrichment of a few percent--a good reactor fuel but not explosible as a bomb material--so that shipment to reactor sites can be made without fear of hijacking.

PROJECT 6. FUEL RECOVERY AND PROCESSING

The purpose of this project is to design a method of continuously removing radioactive debris and fissile material from the PACER cavity and to assist in the optimization of a fuel charge designed to produce ^{233}U and/or ^{239}Pu.

RESEARCH RESULTS

All work on Project 6 is in a very preliminary state, but the following comments indicate our initial thoughts.

Analogy with scaled airbursts indicates that the debris will be largely micron size particles which will remain suspended until striking a wall or being filtered out. The fraction of the debris striking walls, and presumably sticking, is not yet known. Solid particles which make their way through the heat exchanger can be easily removed from the condensed phase.

At present, no work has been done on the design of a breeding model of the fuel charge, but it is easy to estimate the probable effectiveness of such a design, based on production of two moles of neutrons per kiloton of D-D yield. A 50-kT charge would produce about 11 Kg of ^{233}U or ^{239}Pu if half the neutrons could be captured in fertile material. This seems a reasonable expectation, since capture can occur at fireball temperatures where the capture cross section is large. The great advantage of PACER over conventional fission reactor breeders is shown in Figure 5.

It has been noted that ^{233}U produced in a PACER facility is not contaminated with high-energy gamma ray sources, unlike ^{233}U produced in reactors. This will be an important element, along with the security advantages mentioned under Project 5, in making ^{233}U a desirable fuel, both for reactors and for use in PACER fuel charges.

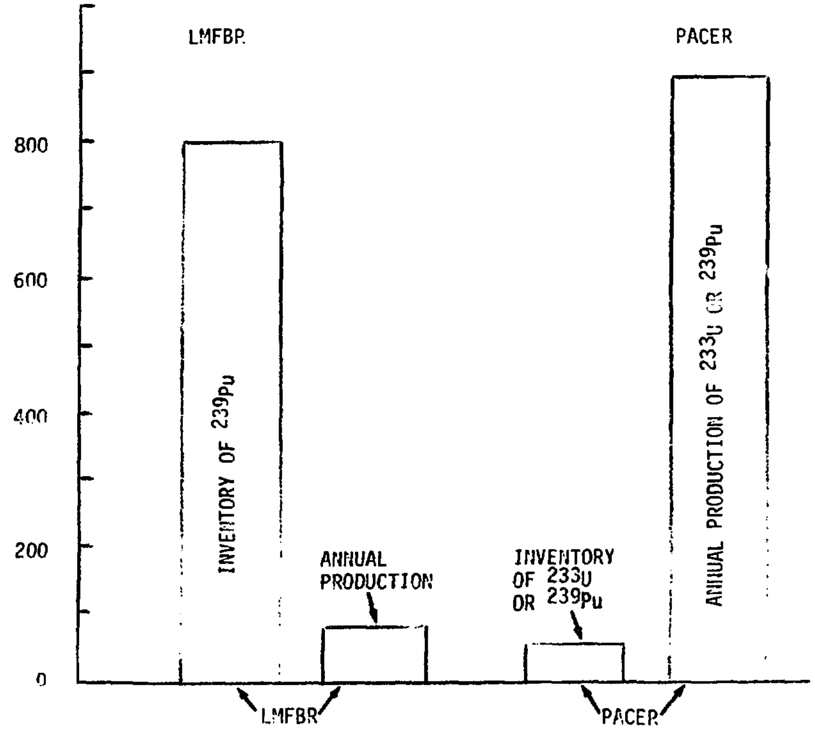

FIGURE 5. COMPARISON OF LMFBR AND PACER AS BREEDERS, EACH TYPE SUPPLYING 200 GW(e); i.e., HALF THE 1974 U. S. CAPACITY (VALUES ARE IN METRIC TONS.)

PROJECT 7. GEOLOGY, SITE SELECTION, AND CAVITY CONSTRUCTION

The purpose of Project 7 is to develop site criteria and select prime sites for experimentation and development.

RESEARCH RESULTS

Geology and Site Selection

The geology of the Gulf Coast basin salt dome fields was reviewed, and many pertinent references to this well-studied area have been assembled. A perusal of the domes having a top surface at sufficiently shallow depth to accommodate PACER cavities indicates there are about 166 domes of which 26 are in use. It is believed that perhaps 70 to 100 of the remaining 140 are large enough for the 300-meter diameter cavity. Of course, some can accommodate more than one cavity, or a larger one, and future fuel charge developments may open the possibility of using smaller domes.

Other possible salt dome sites are portions of the Paradox basin in Utah and Colorado, and possibly a newly discovered deposit in Arizona.

The probable sites available in the Gulf Coast region alone, large enough to accommodate the "baseline" 2000-MW(e) plant, can account for an additional 200-GW(e) of capacity--more than enough to meet the national goals for increased nuclear-generating capacity.

Specific sites suitable for hard-rock cavities have not been tabulated, but there are many and they are not limited to a single geographical region.

Cavity Construction

A review of the Payette study [2] with a view to bringing the costs up to date had made it clear that construction of the cavity in salt is not a large part of the power plant investment, and so cannot influence economic feasibility significantly. Technical feasibility was established by the Payette study, insofar as that is possible without experimentation.

Construction of cavities in rock is more complicated since the rock must be supported as construction proceeds. Studies made in the early 60's are optimistic about technical feasibility (see Appendix D), but cost projections are probably not reliable nor comparable with costs at the Nevada Test Site. This subject received only cursory attention during the first year.

PROJECT 8. NUCLEAR TEST FACILITY

The purpose is to study the feasibility of using a large decoupling cavity as a permanent test facility.

RESEARCH RESULTS

All the considerations regarding the geology and cavity excavation undertaken for PACER apply to this application as well. Only preliminary considerations have been made specifically to this project, and they are presented in the PACER Program Documents DOS-1-81 and DOS-1-82 [10, 11].

PROJECT 9. SYSTEM ANALYSIS, COORDINATION AND PLANNING

The purpose of Project 9 is to ensure system self-compatibility, to plan future work, and to investigate potential applications.

RESEARCH RESULTS

Choice of System Parameters

Early in the project, a review of Kennedy's experimental results [7,9] led to lowering the cavity steam pressure from 440 bars to 300 bars to ensure dry steam with no liquid phase. Later, as the very sensitive pressure dependence of the cost of piping became apparent, the pressure was further reduced to 200 bars. The cavity size was decreased to 300 meters in diameter and the device yield to 50 kT to keep the depth below the surface not less than 4 cavity diameters, somewhat arbitrarily. The nominal choices for the critical PACER parameters are now as follows:

Cavity diameter	300 meters
Cavity depth	1200 meters
Device yield	50 kT
Steam pressure	200 ± 20 bars
Steam temperature	525 ± 50°C
Nominal power level	2 GW(e)
Explosion per year @ 2 GW(e)	804 (@ 80% of peak)

As mentioned in Project 4—Economics, the dependence of the major cost elements of the system on the system parameters was determined, at least approximately, so it would be possible to choose these parameters to minimize the cost of electric power (see Appendix F). These optimizations are forced in the direction of large cavities at shallow depths because the cost of piping quickly dominates as the depth, and, hence, the pressure increases. The above choice of pressure and yield represent minimum cost assuming a fixed 300-meter diameter cavity and $100K fuel charge cost. All this is very rough but does give assurance that the system choices are not only reasonable choices technically, but also tend to minimize power costs.

Planning

Detailed plans for Phase I have been made through RDA inputs to DOS-1-81 [10], the PACER program document. This includes detailed laboratory experiment planning, as well as planning theoretical and design work.

Preliminary planning for a Phase II experimental program was begun (see Appendix F). Basically, the plan is to negotiate for the use of part of a salt mine for initial tests in a 10-meter diameter cavity and proceed immediately to a 100-meter cavity construction by 1976. The cost, including construction and non-nuclear testing and instrumentation is 20 to 30 million dollars.

Potential Applications

An application of PACER technology leading to the most rapid buildup of nuclear-based electric power has been suggested.

As already pointed out, the abundant neutrons available from the D-D reaction make possible the operation of a PACER facility primary as a producer of reactor fuel with power as a by-product. The nominal 2-GW(e) PACER could supply fuel for eight 1-GW(e) reactors. By utilizing thorium as the fertile material, the fuel would be in the form of clean ^{233}U which would then be made secure from theft (as pointed out in Project 5 by dilution to a few percent with natural uranium. This would all be accomplished at a single site, while the reactors which burn the ^{233}U could be located close to the users of power, thus eliminating transmission problems. The design and construction of these reactors--burners, not breeders--would be relatively simple because neutron economy is not an issue. In this mode of operation the approximately 100 available salt dome sites could provide for 1000 GW(e) of additional nuclear power, 200 GW(e) in the south provided by PACER plants, and the remaining 800 GW(e) from ^{233}U burner reactors.

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PROJECT PACER FINAL REPORT - APPENDIXES

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APPENDIX A. PROJECT 2--CAVITY PHENOMENOLOGY

A.1 LOW-TEMPERATURE RADIATION PROPERTIES (F. Gilmore, R. Turco, R. Lindgren)

A preliminary qualitative look was taken at the low-temperature radiation properties of various possible working fluids, since these properties are critical in determining the thermal radiation pulse that gets to the cavity wall. Judging by their electronic states, hydrogen, helium, nitrogen, sulfur vapor, argon, steam, and carbon dioxide will all be quite transparent to visible radiation at temperatures up to several thousand degrees, and methane also up to almost as hot. Accordingly, the thermal pulse will probably penetrate these gases and melt some of the cavity wall. (Moreover, sulfur is a liquid at the desired steady-state temperature and pressure, which makes it quite unsuitable for this application.) Air is different because when heated it forms nitrogen dioxide (NO_2), which is opaque in the visible. Using air opacities based on equilibrium NO_2 concentrations, LASL has calculated a very small thermal pulse at the wall. We have verified qualitatively that this result is reasonable, and that the NO_2 reaction rates in this situation are fast enough to keep the air opaque, even though photodissociation can reduce the NO_2 concentration to 20% of its equilibrium value. In general, if one wishes to minimize the thermal pulse on the wall one should use a mixture like nitrogen/oxygen, nitrogen/steam, nitrogen/carbon dioxide, or possibly nitrogen/graphite dust or argon/graphite dust.

A.2 RADIATION PROPERTIES OF WATER VAPOR RELEVANT TO PACER (F. Gilmore)

To heat salt from 800°K to its melting temperature of 1073°K requires 4.1 kcal/mole, while the latent heat of melting is 6.7 kcal/mole [1]. Since the molecular weight of salt is 58.4 and its density is 2.17 g/cm^3, one can easily calculate that to heat a layer around the outside of a 200 m radius cavity to melting requires 0.8 kilotons/cm, and to melt it completely requires an additional 1.2 kilotons/cm. Hence, if a few percent or more of the energy of a 100 kiloton burst were emitted as thermal radiation, penetrated the colder gas to reach the wall, and were absorbed in the first few centimeters of salt, serious changes in the cavity size and shape due to melting would occur after a few hundred bursts. If instead, as seems more likely, the absorption mean free path for thermal radiation (mostly visible radiation) in the salt is of the order of a meter, the first few bursts would not be enough to cause melting, but the heat would build up over many bursts, since the thermal diffusivity of salt is only about 1 m^2/10 days, so that the long-term melting rate would be almost as great as if the salt were more absorptive. (We are planning some numerical calculations to verify this conclusion.)

Accordingly, it is important to determine if a significant fraction of the energy of a fireball in dense water vapor is emitted as thermal radiation, and if much of this penetrates the colder vapor outside of the fireball.

The behavior of the fireball before radiative cooling becomes important depends upon the thermodynamic and radiative properties of the working fluid at temperatures so high that the molecules are completely dissociated and most atoms are multiply ionized. Since air and water (as well as carbon dioxide and most other gases of interest) have roughly the same number of atoms per molecule and electrons per molecule (within a factor of 1.5), and the same average atomic number of the high-Z atoms (within 20 percent), the corresponding fireballs will have roughly the same size and temperature history. Thus, we can use the temperature profiles calculated for a fireball in dense air [2,3] to estimate the thermal radiation from a fireball in dense water vapor.

At early times the fireball is small but very hot, while later it is larger but less hot, so that we cannot immediately guess which time period contributes the most to the thermal radiation. However, at these densities the gas opacity becomes so large at several thousand degrees (see below) that this limits the fireball surface radiating temperature. Accordingly, the thermal pulse is dominated by the emission after the fireball expands to near pressure equilibrium (about 0.1 sec under PACER conditions), because then the surface area is much larger and the duration is longer.

Table 1 shows the equilibrium composition of water vapor at 320 bars pressure and temperatures between 2000 and 8000°K [4]. These calculations include a mole fraction of 7.2×10^{-5} salt, which is the equilibrium amount that would dissolve in the water vapor at 775°K and 300 bars (before the burst), according to the measurements of Sourirajan and Kennedy [5]. Except for a few isolated Na lines, the only important absorbing species in the visible at temperatures below 6000°K are the negative ions H^-, O^-, OH^- and O_2^- (Cl^- absorbs only in the ultraviolet). These ions have large photoabsorption cross sections throughout the visible wavelengths, as shown in Fig. 1. By multiplying these cross sections by the corresponding concentrations one can readily show that the visible mean free path is many meters at 2000°K, several meters at 3000°K, and rapidly becomes less than a meter above 3800°K, primarily due to the photoabsorption of OH^- (where the attached electrons come from ionization of the sodium). According to the fireball calculations for compressed air [2,3], after pressure equilibrium the edge of the fireball has a temperature gradient $d \ln T/dr = 0.15 \text{ m}^{-1}$. Integrating inward through this gradient, we find the one mean-free-path point to occur at about 3950°K. Since the radius at this point is 60 m, the total black-body emission rate in the visible is 0.03 kilotons/sec. Hence, in the few seconds before the fireball cools due to mixing, probably only a few tenths of a kiloton of thermal energy is radiated by the fireball.

In order to verify this approximate result, multifrequency radiation-hydrodynamic calculations should be made for a 100 kiloton burst in dense water vapor. For this purpose, values of the absorption coefficient at temperatures of a few thousand degrees are required. In calculating the absorption coefficient it is most important to include the absorption of OH^-, H^-, O^- and to a lesser degree O_2^-, and to include the ionization of sodium from the salt, which increases the concentrations of these species. The absorption of other molecules, like H_2O, OH, H_2, O_2 and NaCl, is very small in the visible, and probably can be neglected even in the ultraviolet, because the ultraviolet absorption of the negative ions at the lower temperatures and of neutral atoms at higher temperatures is already so great as to prevent appreciable radiative transfer. In the infrared, H_2O and OH are so opaque that rough estimates of the absorption coefficient should be adequate to cut off radiative flow. Thus, by considering the purpose for which the opacity results are to be used, the labor involved in obtaining them can be greatly reduced by not striving for accuracy in unimportant regions.

The thermal pulse from the fireball may be further attenuated on passing through the outer 140 m of water vapor at about 800°K and 0.12 g/cm^3. The infrared absorption table of Ludwig [9] for water vapor at low densities and several temperatures shows that all radiation of wavelengths greater than 1.1 microns would be attenuated by over an order of magnitude by this much water vapor. The effect of the higher vapor density in the cavity, which can cause formation of water dimers, etc., will be to increase the opacity, as shown by comparison of Ludwig's values for water vapor at room temperature with those of Hale and Querry [10] for liquid water.

The absorption coefficient of water vapor between 0.21 and 1.1 microns is very small, and I have been unable to find any published measurements. Results for the extinction coefficient K of *liquid* water have recently been compiled and evaluated by Hale and Querry [10], and their recommended values are shown as the solid curves in Fig. 2. Since the absorption coefficient equals $4\pi K/\lambda$, where λ is the wavelength, a K value of about 2×10^{-9} corresponds to one mean free path through the outer fluid in the PACER cavity. Thus, if the dense warm vapor behaves like liquid water at room temperature, there will be a "window" between about 0.4 and 0.55 microns through which about half of the thermal pulse discussed earlier will pass. The difference in density may make this window a little wider in the vapor. This effect is unlikely to be large because the absorption rises so steeply on both sides of the window that halving the absorption would hardly change the window width, and because even in the liquid the "bumps" in the curve at 0.6-1.0 microns occur where the overtones of the free H_2O molecule would be expected while below 0.2 microns the absorption coefficient agrees quite well with that measured in the gas [1]. The increase of temperature from the 300°K measurement situation to the 800°K cavity situation probably makes the window only slightly narrower, since theoretical considerations suggest that absorption from electronically or vibrationally excited levels will still be negligible compared to ground-level absorption throughout the visible, leaving only rotational broadening of a few hundred wavenumbers at the most.

It has been suggested that a high-temperature absorption cell be built and measurements be made of water vapor at 800°K and 300 bars with a path length of 2 m. Unfortunately, assuming that 2% absorption could be measured, this would not allow determination of the depth or exact width of the expected optical window, since this sensitivity corresponds to 4×10^{-9} on the scale of Fig. 2. In view of this experimental limitation, the probability that the window is nearly the same as in liquid water, and the estimated cost of the experiment ($100 K), it cannot be recommended at the present time. A much simpler though not so obviously relevant experiment is suggested: observe room-temperature liquid water in a spectrometer cell (which L. Jones of LASL has already done) and compare it with hot liquid water.

A bigger optical uncertainty in the PACER program concerns the absorption and scattering of visible radiation by the salt. It seems very desirable to design and carry out an experiment to measure these properties for several samples from actual salt domes. Because scattering is probably much larger than absorption for rock salt, this experiment would not be trivial.

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Table 1. Equilibrium Composition for Water Vapor with 7.2 x 10^{-5} Mole Fraction of Salt, at a Pressure of 320 Bars.

Concentrations in particles/cm^3

Species	Temperature (^{o}K)						
	2000	3000	4000	5000	6000	7000	8000
E-	7.98E+09	1.97E+13	5.87E+14	3.56E+15	6.75E+15	1.26E+16	3.92E+16
NA	2.60E+14	2.87E+15	6.83E+15	5.75E+15	1.45E+15	4.23E+14	3.13E+14
NA+	7.90E+11	1.36E+14	2.44E+15	9.40E+15	1.16E+16	9.03E+15	7.72E+15
CL-	7.12E+11	9.89E+12	1.55E+13	1.21E+13	4.63E+12	2.36E+12	2.55E+12
CL	1.53E+14	1.80E+15	4.95E+15	7.35E+15	7.98E+15	7.54E+15	6.80E+15
CL+	1.88E-08	1.46E+01	6.27E+05	4.26E+08	5.03E+10	1.20E+12	6.61E+12
H-	2.06E+06	2.42E+11	3.82E+13	4.54E+14	9.28E+14	1.35E+15	2.96E+15
H	2.80E+15	1.06E+18	1.78E+19	7.54E+19	1.43E+20	1.74E+20	1.74E+20
H+	4.10E-09	3.07E+02	1.41E+00	3.76E+11	9.56E+13	3.39E+15	2.29E+16
O-	4.77E+07	2.18E+12	2.03E+14	1.70E+15	2.64E+15	3.06E+15	5.58E+15
O	7.36E+14	4.36E+17	8.76E+18	3.99E+19	7.67E+19	9.13E+19	8.95E+19
O+	9.02E-10	1.08E+02	5.97E+07	1.72E+11	4.43E+13	1.54E+15	1.02E+16
NACL	7.62E+15	2.92E+14	3.46E+13	3.93E+12	2.14E+11	1.82E+10	4.82E+09
NAO	1.66E+13	5.26E+14	1.86E+15	1.48E+15	2.45E+14	3.81E+13	1.43E+13
HCL	7.55E+16	5.19E+16	3.12E+16	1.49E+16	5.66E+15	1.99E+15	7.50E+14
NAH	1.18E+12	9.61E+13	5.72E+14	6.51E+14	1.42E+14	2.78E+13	1.26E+13
CL2	1.51E+10	1.67E+10	1.19E+10	6.58E+09	3.13E+09	1.46E+09	7.32E+08
NA2	1.59E+08	4.14E+09	9.82E+09	3.70E+09	1.37E+08	7.26E+06	2.44E+06
O2-	2.00E+08	2.00E+12	7.68E+13	2.96E+14	1.98E+14	9.61E+13	7.97E+13
O2	4.19E+17	6.84E+18	2.02E+19	2.28E+19	1.25E+19	4.67E+18	1.67E+18
O2+	9.39E-03	1.50E+06	2.60E+10	7.27E+12	2.83E+14	1.93E+15	3.30E+15
H2	1.02E+18	2.05E+19	7.21E+19	9.54E+19	6.24E+19	2.79E+19	1.15E+19
OH-	7.06E+10	1.02E+14	1.52E+15	3.39E+15	1.63E+15	6.40E+14	4.57E+14
OH	3.66E+17	1.38E+19	6.31E+19	9.43E+19	6.42E+19	2.85E+19	1.16E+19
OH+	4.61E-06	2.13E+04	2.12E+09	1.76E+12	1.47E+14	1.80E+15	4.72E+15
NAOH	7.54E+16	5.02E+16	2.45E+16	5.01E+15	2.57E+14	1.41E+13	2.22E+12
HOCL	3.02E+13	1.02E+14	1.21E+14	6.70E+13	1.99E+13	4.44E+12	1.04E+12
CLO2	3.82E+07	6.76E+09	5.59E+10	9.67E+10	5.91E+10	2.13E+10	7.11E+09
H2O	1.16E+21	7.23E+20	3.91E+20	1.29E+20	2.36E+19	3.21E+18	4.74E+17
HO2	1.92E+14	2.39E+16	1.77E+17	2.73E+17	1.34E+17	3.57E+16	6.70E+15
O3	7.11E+09	1.06E+13	2.62E+14	8.11E+14	6.10E+14	2.13E+14	6.31E+13
NA2CL2	7.78E+11	3.78E+07	1.10E+05	6.12E+02	1.13E+00		
TOTAL	1.16E+21	7.66E+20	5.73E+20	4.58E+20	3.83E+20	3.30E+20	2.89E+20

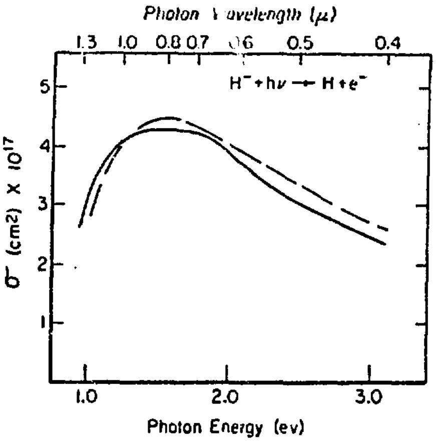


Fig. 1a. Photoabsorption cross section of H^- from Smith and Burch [6].

Note: Improved values were published later, but these are adequate for present purposes.

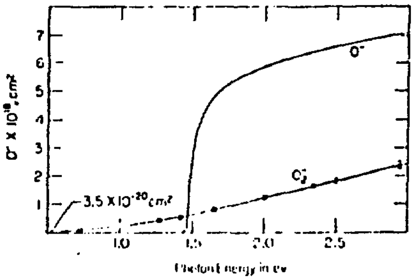


Fig. 1b. Photoabscrption cross sections of O^- and O_2^- from Burch, Smith and Branscomb [7].

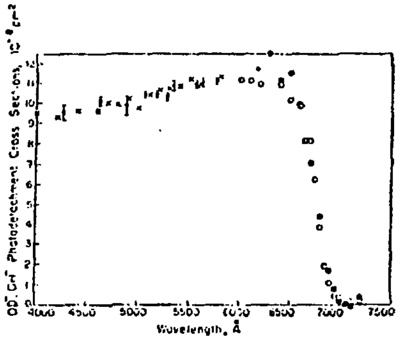


Fig. 1c. Photoabsorption cross sections of OH^- (solid points) and OD^- (crosses and circles) from Branscomb [8].

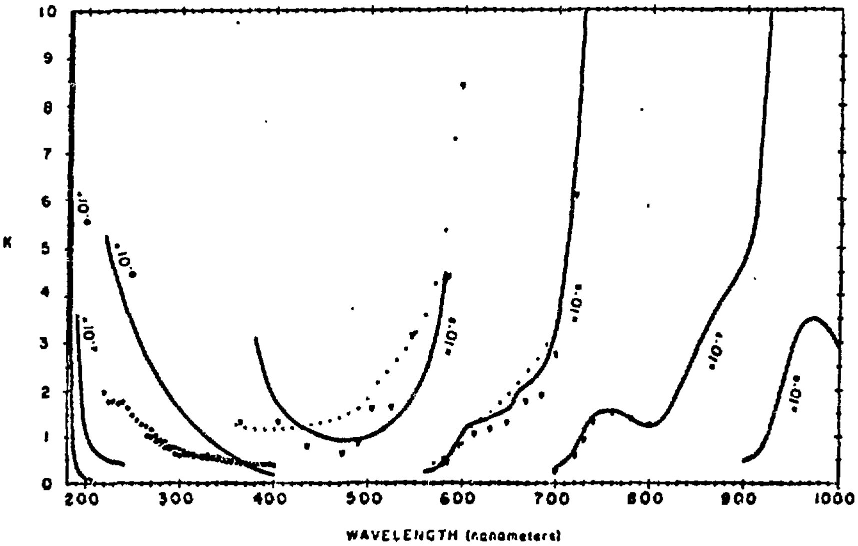


Fig. 2. Extinction coefficient K of liquid water near 300°K recommended by Hale and Querry [10], solid curves. (Points refer to the three sets of data that disagree significantly with the solid curves, but most of the data agree.) The linear absorption coefficient equals $4\pi K/\lambda$.

A.3 PACER WORKING FLUID AND NEW OPERATING CONDITIONS (H. Hubbard)

During a meeting at RDA on 21 September 1973, the use of water as a working fluid was discussed both from the standpoint of its thermodynamic properties in equilibrium with salt, and the corrosive properties of the solution in contact with steel. The attendees were

RDA

D. Dee
F. Gilmore
L. Gore
D. Griggs (Consultant)
H. Hubbard
G. Kennedy (Consultant)
A. Latter
R. Lindgren
E. Martinelli
R. Turco

LASL

A. Nutt
R. Shreffler

The principal source of information discussed was a paper by S. Sourirajan and G. C. Kennedy in the American Journal of Science, Volume 260, February 1962, on "The System H_2O-NaCl at Elevated Temperatures and Pressures." This work shows that the working pressure within a salt cavity is limited at a given temperature by the presence of the salt. Addition of H_2O increases the pressure up to the point at which liquid salt solution begins to form and no further increase in pressure occurs. Lower pressures are admissible without involving the presence of any liquid.

A.3.1 Corrosion

During the course of the experiments described in the paper mentioned above, Kennedy states that his stainless steel piping suffered no corrosion at all. He was so surprised at this result that he decided to find out why, and discovered that a spinel coating forms on the pipes which protects them. This result is significant for PACER in that stainless steel becomes the logical piping material.

A second byproduct of the Kennedy-Sourirajan work was that no formation of NaOH and HCl in measurable (by pH tests on samples) amounts was formed. There are thus no excess OH^- radicals to penetrate grain boundaries and damage the salt integrity.

These two results have removed the major objections to the use of H_2O as working fluid, which is otherwise very desirable. We therefore propose to consider H_2O, tentatively, and with the probable addition of air to facilitate NO_2 production, as the chosen working fluid.

A.3.2 Operating Conditions

The operating temperature is chosen as high as is consistent with maintenance of strength in good stainless steels; which is in the neighborhood of 525° to 550°C. This allows some temperature swing. The operating pressure is now constrained by the thermodynamics of the NaCl-H_2O system to lie below 360 to 380 bars if we are to avoid condensation on the cavity walls.

We have chosen an average operating point which keeps the expected pressure and temperature excursions well within the gas phase. The salt concentration is so low that the density (which was not measured by Kennedy) has been taken from the steam tables with very little error expected. (Values near the critical point, p = 220b, T = 375°C are expected to be incorrect by large factors even with a fraction of a percent of NaCl present.) Our chosen conditions are as follows:

Mean temperature	525 to 550°C
Temperature swing	± 27°C
Mean pressure	320 bars (4700 psi)
Pressure swing	± 22 bars
Density of steam	0.115 gm/cm^3
Depth of center of cavity	1.45 km = 4760 feet

Cavity volume	3.0×10^7 m^3
Mass of H_2O	3.4×10^{12} gm
Energy yield per pulse	100 kilotons

These new conditions will result in decreased costs for piping and for cavity mining, but will result in a slightly increased seismic effect.

A.4 PACER SHOCK REFLECTION AT CAVITY WALL (R. Lindgren)

The state of the gas behind the reflected shock was determined as a function of the pressure behind the incident shock. Representing the ambient state by subscript 0, the state behind the incident shock and in front of the reflected shock by subscript 1, and the state behind the reflected shock by subscript 2, the Hugoniot relations expressing the change of state across the shocks can be written as

$$e_1(p_1,V_1) - e_o(p_o,V_o) = \frac{1}{2}(p_1+p_o)(V_o-V_1), \qquad (1)$$

$$e_2(p_2,V_2) - e_1(p_1,V_1) = \frac{1}{2}(p_2+p_1)(V_1-V_2), \qquad (2)$$

where p is pressure, V specific volume, and e specific internal energy. The difference between fluid velocities on the two sides of the shock is given by

$$\Delta u_{o1} = [(p_1-p_o)(V_o-V_1)]^{1/2}.$$

The boundary condition for reflection at a rigid wall requires that the velocities satisfy $\Delta u_{o1} = \Delta u_{12}$, or

$$(p_2-p_1)(V_1-V_2) = (p_1-p_o)(V_o-V_1). \qquad (3)$$

For the ambient conditions given on the following table, the calculations were carried out by specifying p_1 and solving (1) for V_1. Knowing p_1 and V_1, (2) and (3) were solved simultaneously for p_2 and V_2.

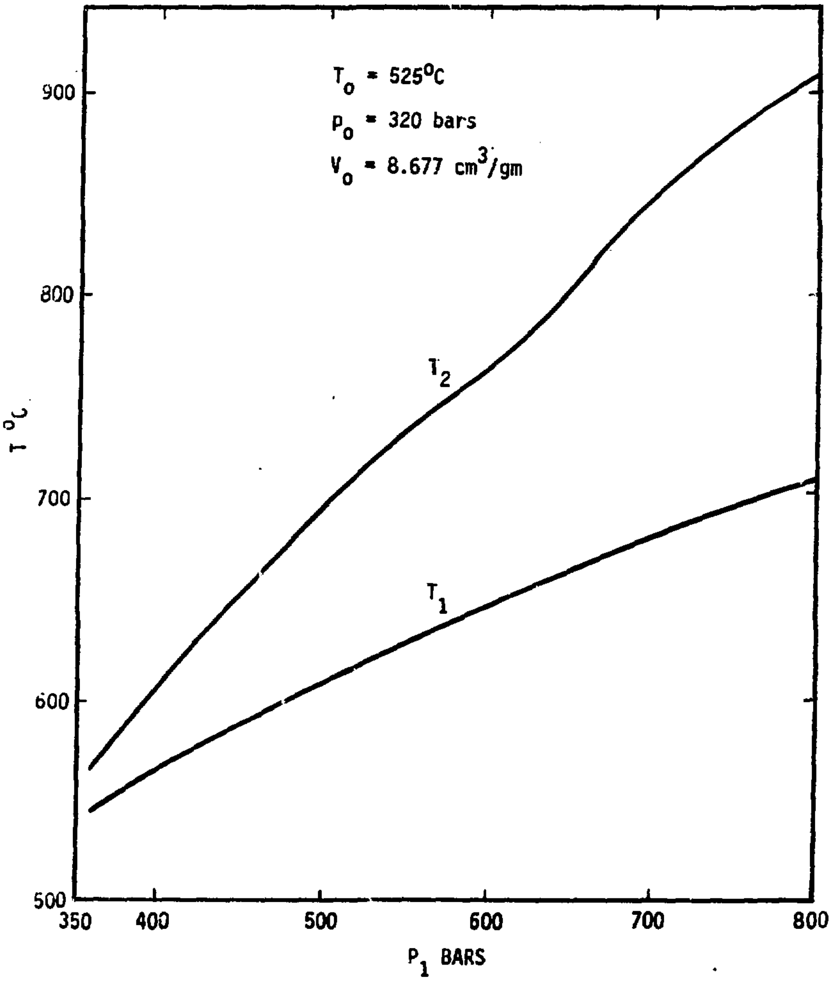
Examination of the H_2O-NaCl system described by Sourirajan and Kennedy shows that the gas behind the shock waves would be unsaturated and that neither solid NaCl nor liquid could form. Since the salt content is relatively small and the state of the system is far removed from the liquid region, the gas may be treated as pure steam in evaluating its thermodynamic properties. Data for $e(p,V)$ of steam were obtained from reference (1) for $p < 1000$ bars and from reference (2) for $p > 1000$ bars. The internal energies from these two sources were related by $e(\text{Keenan}) - e(\text{Sharp}) = 107$ joules/gm. This difference in energies is primarily attributable to different choices for the zero of energy but is somewhat arbitrary as a result of discrepancies between the two data sources. The values of internal energy in the following table assume the internal energy of liquid water is zero at the triple point.

HUGONIOT RELATIONS FOR REFLECTED SHOCK

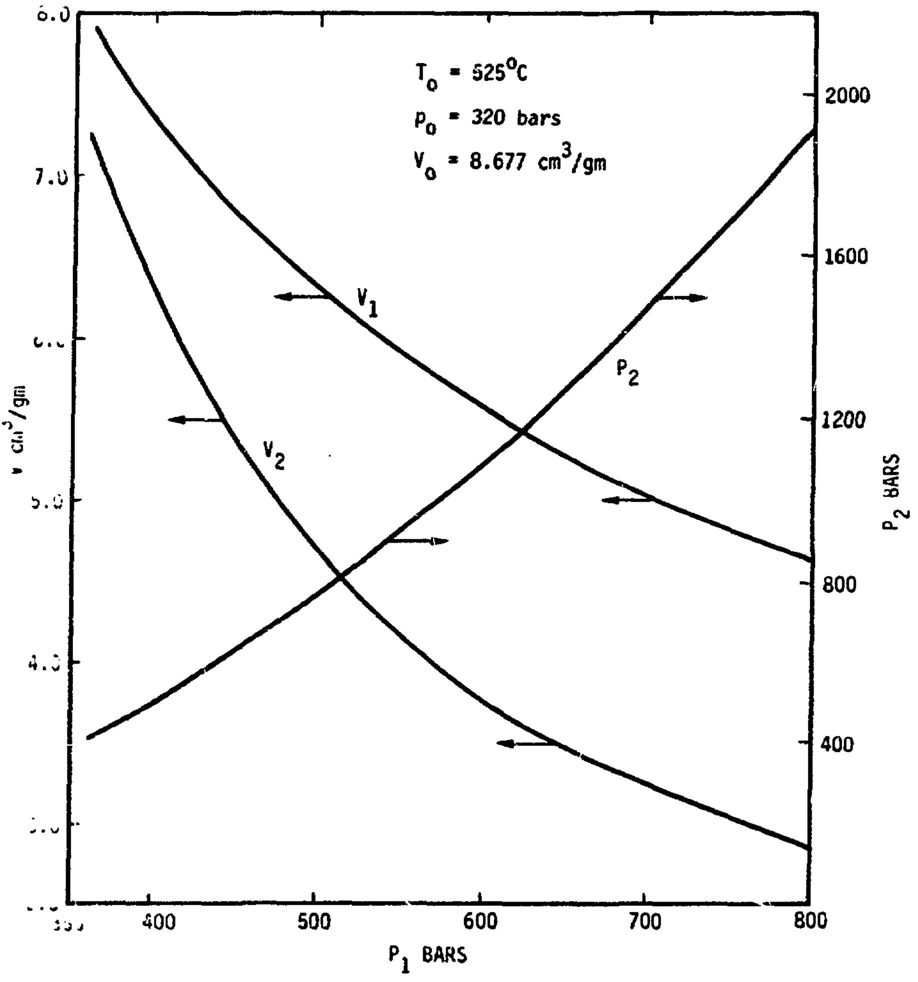
Ambient conditions:

$T_o = 525^\circ C$
$p_o = 320$ bars
$V_o = 8.677$ cm^3/gm
$\rho_o = 0.1152$ gm/cm^3
$e_o = 2876$ joules/gm
$h_o = 3154$ joules/gm

p_1	V_1	ρ_1	T_1	e_1	p_2	V_2	ρ_2	T_2	e_2
360	7.94	0.126	546	2898	406	7.27	0.138	568	2923
400	7.36	0.136	566	2922	498	6.29	0.159	608	2970
450	6.78	0.148	589	2949	626	5.37	0.186	653	3023
500	6.29	0.159	610	2974	767	4.68	0.214	695	3075
550	5.89	0.170	629	2997	921	4.16	0.240	734	3120
600	5.55	0.180	647	3019	1084	3.74	0.267	764	3171
650	5.27	0.190	664	3041	1271	3.46	0.289	806	3215
700	5.02	0.199	680	3063	1479	3.23	0.309	849	3257
750	4.81	0.208	695	3083	1695	3.04	0.329	882	3298
800	4.61	0.217	709	3103	1909	2.86	0.350	908	3341



Reflected Shock Hugoniot Relations



Reflected Shock Hugoniot Relations

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A.5 EFFECT OF SALT EVAPORATION ON REFLECTED SHOCK (R. Lindgren)

The following calculations are made to determine whether evaporation of salt from the cavity wall during the time the shock encounters the wall is sufficient to affect the strength of the shock or to evaporate a significant amount of salt. The length of interest is denoted by ℓ, and it may be the length of the pressure pulse, the region of maximum temperature, or the thickness of the shock front. Its magnitude is not of particular importance, because the time of contact with the wall and the volume of disturbed gas are both proportional to ℓ, and it cancels from the problem in determining the net effect on the disturbance. Throughout the calculations conditions are chosen to maximize the effect, and hence the results are conservative estimates.

In obtaining an upper bound on the time the shock is in contact with the wall, the shock velocity is assumed to equal the sonic velocity at 525°C. For a perfect gas with constant heat capacities, $c = (\gamma RT/M)^{1/2} \approx 6.9\text{x}10^4$ cm/sec. In estimating the evaporation rate from the wall, limitations imposed by heat transfer from gas to wall are neglected, and the wall temperature is taken as 925°C. Calculations of Hugoniot relations in Section A.4 show this temperature to be attained by the reflected shock only when the pressure of the incident shock is greater than 800 bars. Ideal-gas calculations show that the NaC vapor pressure at this temperature would yield an equilibrium gas concentration of $N = 2.7\text{x}10^{16}$ molecules/cm^3. The evaporation rate from the solid is the same as it would be in an equilibrium situation in which evaporation was balanced by condensation. The flux to the wall is given by $J = N\bar{v}/4$ where $\bar{v} = (8kT/\pi m)^{1/2}$ and would equal the condensation rate if every molecule hitting the wall were to stick. Taking J as the evaporation rate and assuming a temperature of 925°C, the values $\bar{v} = 6.6\times10^4$ cm/sec and $J = 4.4\times10^{20}$ molecules/cm^2-sec are obtained.

Assuming the evaporated NaCℓ to be uniformly distributed over the region of length ℓ, the additional concentration produced in a time $\tau = \ell/c$ is given by

$$\Delta N = J\tau/\ell = J/c = 6.3\times10^{15} \text{ molecules/cm}^3.$$

Since the concentration of NaCℓ in the steam is 3.2×10^{17} molecules/cm^3 at 525°C and 320 bars and increases in proportion to pressure in the shock, the maximum fractional increase in concentration is about 0.008. For solid NaCℓ with density $\rho_s = 2.165$ gm/cm^3, the thickness δ of NaCℓ removed is given by

$$\delta = \frac{MJ\tau}{N_o\rho_s} = \frac{MJ\ell}{N_o\rho_s c} = 2.8\times10^{-7}\,\ell\ ,$$

where M is molecular weight and N_o is Avogadro's number.

The effect of evaporation on the shock temperature can be calculated from values of the heat capacity C_p of steam and the heat of vaporization λ of NaCℓ. C_p is about 0.64 cal/gm-°C, $\lambda = 50000$ cal/mole at 925°C, and a maximum effect is achieved by choosing $\rho = 0.115$ gm/cm^3. Then

$$\rho C_p \Delta T = \frac{\lambda J\tau}{N_o\ell}$$

or

$$\Delta T = \frac{\lambda J}{N_o c \rho C_p} = 0.007^\circ\text{C}.$$

This is the maximum average temperature change that could occur in a layer of thickness ℓ as a result of salt evaporation.

Conclusion

The calculated effect is negligible and would likely be less by orders of magnitude if heat transfer limitations were imposed and if the evaporation-rate determination did not assume that every molecule to strike the surface would condense. The effect increases rapidly with temperature, but the Hugoniot calculations (see Section A.4) show that the temperature increases rather slowly with incident shock pressure. At a temperature of 1413°C (boiling point of salt), the effect would be greater by about three orders of magnitude.

A.6 FORMATION OF LIQUID NaOH IN PACER CAVITY (R. Lindgren)

This discussion is presented to summarize our present knowledge of the formation of liquid NaOH in the salt cavity with steam as the working fluid. The presentation below is based on a comparison of ideal-gas calculations with NaCℓ solubility data and on a certain amount of speculation and experimental evidence. No serious investigation of the matter has been undertaken at RDA, but it was thought that a brief presentation of the considerations involved might add some perspective to the problem.

A.6.1 Equilibrium Relations

The major chemical species in the cavity are involved in the reaction

$$H_2O + NaC\ell \rightleftharpoons HC\ell + NaOH.$$

At equilibrium the concentrations of the species obey the relation

$$\frac{(HC\ell)(NaOH)}{(H_2O)(NaC\ell)} = K, \tag{1}$$

where K is virtually independent of composition. Since NaCℓ is in equilibrium with the solid phase, its concentration is given by

$$(NaC\ell) = K_1. \tag{2}$$

Also, condensation of liquid NaOH places an upper limit on the gaseous NaOH concentration, which is consequently constrained by the relation

$$(NaOH) \leq K_2. \tag{3}$$

Liquid NaOH is present only if $(NaOH) = K_2$. These relations together with equations for the conservation of elements determine the concentrations.

A.6.2 Ideal-Gas Calculations

Ideal-gas calculations predict HCℓ and NaOH concentrations somewhat in excess of the NaCℓ concentration at our nominal conditions ($T = 525^{\circ}C$, $\rho = 0.115$ gm/cm^3). Liquid NaOH would be formed, but the total amount of solid NaCℓ dissolved would be small (about 10^{13} molecules/cm^3 compared to a water concentration of $4x10^{21}$).

A.6.3 Real Gas Behavior

The actual solubility data of Sourirajan and Kennedy predict a much higher value of NaCℓ with $K_1/K_{1\ ideal} > 10^5$. This effect can be represented in thermodynamic relations as a modification of the chemical potential of NaCℓ arising from attraction of the polar molecules NaCℓ and H_2O. Introduced into Eq. (1), this effect reduces the equilibrium constant below its ideal value by the same factor by which (NaCℓ) is increased. Consequently the values of (HCℓ) and (NaOH) are unchanged, but they are very small relative to the value of (NaCℓ). However, HCℓ and NaOH are also polar molecules, and it is expected that their interaction with H_2O would affect their chemical potentials in a similar manner. While this effect would tend to increase the concentration of NaOH in the gas phase, it would decrease its tendency to condense to liquid NaOH. Without experimental evidence it cannot be determined whether liquid NaOH would form under the conditions in the salt cavity.

The evidence presently available consists of information by Kennedy on experimental work done in preparation of Reference 1. In the two-phase region (gas and salt-water solution), the formation of large amounts of HCℓ and NaOH would lead to excess HCℓ in the gas and excess NaOH in the liquid. Quantitative calculations of this partitioning have not been made, but Kennedy's pH measurements of samples taken from the liquid and the gas phases showed no measurable deviation from neutrality, indicating that the amount of HCℓ and NaOH in the system could not greatly exceed the ideal-gas prediction (about $6x10^{12}$ molecules/cm^3).

A.6.4 Conclusions

The available evidence indicates that the amount of HCℓ and NaOH in the cavity does not greatly exceed ideal-gas predictions. It is not known whether or not the gas is saturated with NaOH, whether the small amount present would condense if supersaturated, or whether liquid NaOH would be formed directly at the cavity wall. Depending upon the concern over liquid NaOH, further investigation is probably warranted.

References

Sourirajan, S. and G. C. Kennedy, "The System H_2O-NaCℓ at Elevated Temperatures and Pressures," American Journal of Science 260, 115-141 (1962).

A.7 F-CENTERS IN NaCℓ; A SUMMARY OF FACTS RELEVANT TO PACER (Diana Dee)

Color centers, or F-centers (F standing for the German word Farben) can be produced in all crystalline alkali halides. An F-center is a negative-ion vacancy that has trapped an electron; this model is based on the results of experiments which have looked at polarized light absorption, ESR, ENDOR, crystal expansion, addition of metal atoms, and properties of the F'-center (an F-center that has trapped an electron).

When F-centers are produced in NaCℓ, the crystal appears red. (In KCℓ, KBr, KI, CsBr, and CsI, the coloration is blue.) Of course, the absorption maximum (at energy ϵ_m or wavelength λ_m) and the peak width at half maximum (H) are functions of temperature, pressure, and sample treatment subsequent to F-center formation. At room temperature, ϵ_m is 2.67 eV (λ_m is 465 nm) and H is 0.46 eV. Upon increasing the temperature, the violet absorption edge energy remains constant, while ϵ_m shifts to lower energy and H increases. An increase in pressure of less than 1 kbar has practically no effect on ϵ_m. Quantitative measurements of ϵ_m and especially of H are very difficult to perform accurately, because F-band radiation destroys the F-center. All experimental work done so far has been performed using single crystals of alkali halide.

Production of F-centers may be accomplished by a variety of methods, which may be broadly classed into three types: electron injection, additive coloration, and irradiation.

Electron injection is accomplished by applying several hundred volts to a pointed platinum cathode (relative to the crystal). The optimum temperature for this process in NaCℓ is about 640°C; when the colored crystal is cooled to room temperature, it becomes black due to the precipitation of Na atoms. If the crystal is in equilibrium with Na metal vapor or embedded colloid, F-centers may be formed; this process is known as additive coloration. Both electron injection and additive coloration are probably of little interest to PACER.

Many different types of irradiation may lead to the formation of F-centers. To knock a $C\ell^-$ ion completely out of a NaCℓ crystal (thereby creating a negative-ion vacancy) requires 25 eV, but it is not necessary to supply radiation of this energy to create F-centers. There are always some vacancies present at the beginning of the irradiation, and high intensity irradiation creates more vacancies, although the mechanism of this process is unknown for radiation which imparts less than 25 eV of energy to a $C\ell^-$ ion upon collision (i.e., a <645 keV photon or a <400 keV electron, assuming a head-on collision).

The final concentration of F-centers produced depends upon the temperature, the length of irradiation, the type, energy, and intensity of the radiation, the purity of the sample, and the previous treatment of the sample. For experimental convenience, bulk F-center concentrations usually range from the order of 10^{15}/cc to 10^{17}/cc; bulk concentrations from 10^{13}/cc to 10^{18}/cc may be easily produced. (The Na atom concentration in "pure" NaCℓ at room temperature is 2.2×10^{22}/cc.) Concentrations are calculated using Smakula's equation:

$$N_o = 1.3\times10^{17} \frac{H\,n}{(2+n^2)^2} \frac{\alpha_m}{f} .$$

H, the half-width, and α_m, the maximum absorption coefficient, depend on the temperature; n is the index of refraction; and f is an effective absorption oscillator strength. In order to determine α_m one must know the effective thickness of the colored portion of the crystal as well as the reflection losses. Different workers assume different values for f, ranging from .7 to 1.

Bombardment of a NaCℓ crystal with 25 keV electrons at room temperature (for 10 minutes with a beam current of 1.7 $\mu A/cm^2$) produced F-centers in a layer 12 to 18 μ thick with a density of 1×10^{18}/cc. Another study using 5 keV electrons at temperatures from 90°K to 500°K resulted in coloration in a layer only 560 nm thick but with a color-center density of 5×10^{19}/cc.

Thin surface layers of F-centers may also be produced by exciton generation. Excitons are formed by irradiating the crystal in the u.v. region where strong absorption starts (~4.4 eV), thereby exciting electrons from the valence band to the conduction band; an exciton is the excited electron coupled to the hole (missing electron) that it left behind. When the exciton interacts with a negative-ion vacancy (sometimes called an F^+-center), an F-center may be formed. The holes are presumably extremely immobile; they are probably trapped at other types of crystal imperfections. A few tenths of an eV above the absorption threshold the absorption coefficient is high; thus the radiation does not travel very far into the crystal before it is absorbed, and a thin surface layer of F-centers results. Conversely, for radiation a few tenths of an eV below the absorption edge, the coloration extends much farther into the crystal. In either case the resulting density of centers is only about 10^{15}/cc at room temperature.

Water vapor does not absorb at 4.4 eV; of the molecules of possible interest to PACER, O_3, SO_2, and NO_2 are the strongest absorbers there. Thus F-center production by 4.4 eV (290 nm) u.v. irradiation may be important.

F-centers are also produced by x- and γ-irradiation. The concentration (10^{15} to 10^{17}/cc), depth (on the order of 1 cm), and uniformity of the resulting F-center layer depends upon the temperature, irradiation time and intensity, sample purity, and applied stress. It is difficult to quantify the results due to this type of irradiation, because the nature of the bremsstrahlung differs from laboratory to laboratory. Of interest is the fact that F-centers are produced by x-rays at 10°K, although creation of an ion vacancy pair is a prerequisite; this indicates that vacancy pair production is somehow assisted by the radiation.

The Ca^{+2} ion is the most abundant soluble impurity in naturally-occurring NaCℓ. Although the addition of Ca^{+2} to NaCℓ crystals should create <u>positive</u> rather than negative ion vacancies, addition of Ca^{+2} increases the colorability of the crystal and increases the rate of production of the color centers. These effects are not seen when Cd^{+2} is used instead. The presently accepted explanation for the rate and concentration enhancement by Ca^{+2} ion impurity centers is that these centers trap holes, decreasing the probability of excited electron-hole recombination, and thus increasing the probability both of trapping an electron at an F^{+}-center and of producing defects. Crystal expansion measurements have implied that two ion vacancies are produced per F-center formed.

The behavior of the F-center upon irradiation with light within the F-band region of the spectrum is by no means simple. At low temperatures, this bleaching results in the destruction of F-centers and the formation of F'-centers (the result of released electrons being trapped by other F-centers). The F'-band is very broad ($H \approx 2$ eV) and peaks at about 2.4 eV (~520 nm; this at 143°K). Bleaching of F'-centers with F'-light leads to the re-formation of the F-centers. Another result of F-center irradiation detectable only at low temperatures is luminescence, with peak intensity at 1.1 eV (1120 nm) at 77°K. Other absorption bands due to different excited states of the F-center are detectable to the violet of the F-band but their maximum absorption is less than 5% of that of the F-center. They are called K (Kleinschrod) and L_1, L_2, and L_3 (Lüty).

Irradiation at room temperature (RT) produces bands to the red of the F-band which do not arise from the same point imperfection (as does the F'-band). One obtains an almost featureless, broad absorption band at RT, but upon cooling the irradiated crystal to 77°K (NT) one can see the structure of this band. Very short irradiation times produce the A- and B-bands, which appear right next to the F (making H difficult to measure accurately). Formation of these absorption bands is probably due to impurities in the crystal.

Longer irradiations produce the M-band (Molnar) at 1.73 eV (measured at NT). Even longer exposure results in the appearance of either two or six bands between the M and F; these are called R because they appear to the red of F. The set R_1-R_2 appear when the absorption coefficient $k \cong 20\ cm^{-1}$, but the set R_α-R_β-R_γ-R_δ-R_ε-R_ζ appear for $k \cong 2\ cm^{-1}$. Irradiation with K- or M-light enhances the R absorption. Warming to 250°C reduces R absorption and enhances F and K absorption. Irradiation at one of the two (or six) R maxima reduces absorption of all the R's; the M, F, and K absorptions are suddenly enhanced, then gradually decrease to their final equilibrium values. Other complex structures, the N- and O-bands, appear to the red of M. Figure 1 shows these bands in KCℓ (on which it seems that much more work has been done than on NaCℓ); Table 1 lists ε_m and λ_m values for the bands in NaCℓ.

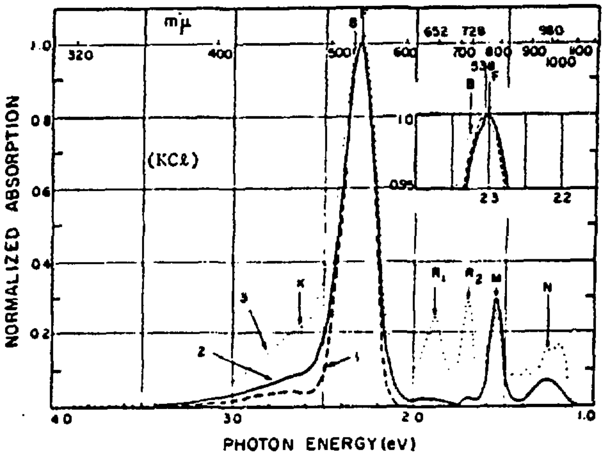

FIG. 1. Effect of bleaching at room temperature on the *F*-band (absorption measurements at NT), curve 1, unbleached, curve 2, 5-min bleaching, curve 3, 1 hr bleaching.

Table 1. Energies (ϵ_m) and wavelengths (λ_m) of Absorption Maxima for Various Color Centers in $NaC\ell$

Center	ϵ_m(eV)	λ_m(nm)
F	2.74 (NT)	452
	2.67 (RT)	465
	2.63 (400°C)	472
F'	~2.4 (NT)	~520
R_1	2.27 "	546
R_2	2.08 "	596
R_ζ	2.34	530
R_ϵ	2.23	556
R_δ	2.16	574
R_γ	2.07	600
R_β	1.99	623
R_α	1.87	663
M	1.73 "	717
N	1.50 "	827

NT is nitrogen temperature, 77°K.

RT is room temperature, ~20°C.

because these bands do not appear when the F-centers are bleached at low temperature, it is speculated that these other color centers are associated with crystal imperfections and aggregates of imperfections. Work with KCℓ has shown that F-centers are in thermal equilibrium with aggregates of F-centers and ion vacancies; heating KCℓ in the dark produces complete conversion of F-centers to aggregates at about 300°C, while heating to 500°C seems to dissociate the aggregates and give the original spectrum. Another experiment has indicated that the rate of bleaching (with white light) is increased by subjecting the colored NaCℓ crystal to a shock wave (.5 μsec, 30 kbar); the plastic deformation increases the number of "traps," speculated to be clusters of ion vacancies, that absorb the electrons which have been optically excited from the F-center to the conduction band. (Photoconductivity work has shown that release of the electron from the first electronic excited state of the F-center to the conduction band is a two-step process. The first step has a lifetime of 10^{-6} sec (two orders of magnitude longer than expected); the second step, which is the alternate pathway to luminescence, involves a net loss of about .1 eV but has an activation energy of about .1 eV.) Recent experiments have led to the conclusion that the M-band is due to the F_2-center. First, an F^+-center and an F-center combine to form an F_2^+-center, with an absorption maximum at about 1000 nm (1.24 eV). Then, the F_2^+-center traps an electron, forming the F_2-center with an absorption maximum at 715 nm.

Bleached crystals "remember" that they have been colored; all traces of coloration can be removed only by heating the crystal to 300°-400° above the temperature at which coloration was produced. This plus the fact that ion vacancy pairs are produced by less-than-25 eV energy implies that diffusion-controlled processes are involved in the formation, aggregation, and destruction reactions associated with the color centers. The rates of all these processes thus are found to depend upon trace impurities, irradiation temperature, and dose rate. For example, increased hole mobility leads to decreased F-center production efficiency in NaCℓ above 200°K; but mobile holes cannot permanently destroy F-centers unless the F^+-centers so produced can move to "annihilation sites."

No experiments have reported significant heating accompanying visible radiation absorption. A simple calculation, assuming extreme conditions (density of centers = 10^{20}/cc, 1.0 eV of energy released as phonon energy per absorption event, a heat capacity for NaCℓ of .2 cal/gm/deg, and <u>all</u> 10^{20} centers/cc absorb at once), predicts an increase in temperature of the absorbing layer of 10°.

The large number and complexity of all the processes involving color center formation and destruction and imperfection diffusion and aggregation make the prediction of the behavior of impure, polycrystalline NaCℓ at high temperature and irradiation difficult, if not impossible. Thus in order to predict the behavior of the PACER cavity wall, experiments should be performed using appropriate samples of naturally-occurring NaCℓ and subjecting these to temperature, pressure, and irradiation conditions most likely to prevail during operation.

There have been many recent articles dealing with the effects of crystal defects and impurities on work-hardening, radiation-hardening, surface-hardening, high-temperature creep, and many other similar phenomena. These effects are probably of relevance to PACER; perhaps someone who is familiar with the field of the mechanical properties of solids should review these articles.

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A.8 COMPOSITION AND THERMODYNAMIC TABLES FOR THE H_2O-NaCℓ SYSTEM (R. Lindgren)

The following is a list of computer output that has been generated for study of conditions in the salt cavity.

1. H_2O + NaCℓ

   T(°K) = 600(50)750(25)800(50)950

   ρ_o = 0.115 gm/cm^3; ρ/ρ_o = 0.2(0.1)1.2

   Real-gas behavior

2. 0.98 H_2O + 0.02 Air + NaCℓ

   Conditions same as above

3. 0.98 H_2O + 0.02 Air + NaCℓ

   T and ρ same as above

   Ideal-gas behavior

4. H_2O + 7.2x10^{-5} NaCℓ

   T(°K) = 1000(1000)16000(2000)24000

   ρ_o = 1 gm/cm^3; $\log_{10} \rho/\rho_o$ = -4.5(0.5)0.5

   Ideal-gas behavior

5. H_2O + 7.2x10^{-5} NaCℓ

   T and ρ same as above

   Real-gas p-V-T behavior

6. $0.99\ H_2O + 0.01\ Air + 7.2x10^{-5}\ NaC\ell$

Conditions same as above

7. $0.97\ H_2O + 0.03\ Air + 7.2x10^{-5}\ NaC\ell$

Conditions same as above

8. $H_2O + 7.2x10^{-5}\ NaC\ell$

$\log_{10}T(^{o}K) = 2.8(0.1)7.2$

$\rho_o = 1\ gm/cm^3;\ \log_{10}\rho/\rho_o = -4.5(0.5)0.5$

Real-gas p-V-T behavior

9. $0.99\ H_2O + 0.01\ Air + 7.2x10^{-5}\ NaC\ell$

Conditions same as above

10. $0.97\ H_2O + 0.03\ Air + 7.2x10^{-5}\ NaC\ell$

Conditions same as above.

The mole fraction NaCℓ of $7.2x10^{-5}$ assigned in the high-temperature runs is the equilibrium amount present at $T = 775^{o}K$ and $p = 300$ bars.

A.9 COMPOSITION AND THERMODYNAMIC TABLES FOR PACER WORKING FLUID

(R. Lindgren)

The following tables are a selection from those generated for study of conditions in the salt cavity. With relative amounts of H_2O, NaCℓ, and air specified as input material, the equilibrium chemical composition, pressure, and thermodynamic functions of the gas mixture were calculated at given temperatures and densities. For clarity of description the tables can be conveniently divided into two sets.

The first set simulates conditions representative of typical cavity operation. Temperatures were from 600 to 950°K, and the gas phase was assumed to be in equilibrium with solid NaCℓ. Gas imperfections were represented in the calculation by the second virial coefficient. Under these conditions of high density and relatively low temperature, the second virial coefficient alone is insufficient to adequately describe the real-gas behavior, and consequently an effective virial coefficient dependent upon temperature and density was obtained from the p-V-T data of Holser and Kennedy to simulate the H_2O-H_2O interaction. Similarly the amount of NaCℓ in the gas phase under such conditions greatly exceeds the ideal-gas prediction, and an effective virial coefficient for the NaCℓ-H_2O interaction was chosen to match the gas-phase solubility data of Sourirajan and Kennedy.

The second set of tables represents conditions which may occur in the fireball. No condensed phases were considered, and the NaCℓ present was the equilibrium amount occurring at a temperature of 775°K and a density of 0.115 gm/cm^3 (p=300 bars). The second virial coefficient for H_2O was obtained using data for the Stockmeyer potential in Hirschfelder, Curtiss, and Bird. No virial coefficient was included for the H_2O-NaCℓ interaction. Nonideal charged-particle interactions were taken into account through the Debye-Hückel correction.

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EQUILIBRIUM COMPOSITION FOR 0.98 WATER + 0.02 AIR + NACL (6500K)

CONCENTRATIONS IN PARTICLES/CM3

SPECIES	LOG10 OF DENSITY RATIO (STANDARD DENSITY = 1.1500E-01 GM/CM3) -.70	-.52	-.40	-.30
E-	5.70E-20	3.45E-20	2.43E-20	1.88E-20
NA	1.14E-03	9.26E-04	8.21E-04	7.62E-04
NA+	1.13E-04	1.53E-04	1.92E-04	2.32E-04
CL-	4.17E-10	3.12E-10	2.52E-10	2.11E-10
CL	2.41E+02	3.01E+02	3.44E+02	3.70E+02
H	5.56E-04	6.16E-04	6.62E-04	7.00E-04
O-	1.06E-26	7.78E-27	6.35E-27	5.47E-27
O	7.73E+01	9.47E+01	1.09E+02	1.22E+02
N	1.43E-16	1.75E-16	2.02E-16	2.26E-16
NACL	9.44E+13	2.71E+15	1.89E+16	4.53E+16
NAO	2.07E-03	2.06E-03	2.10E-03	2.18E-03
HCL	5.38E+09	7.43E+09	9.12E+09	1.05E+10
NAH	4.38E-14	3.94E-14	3.75E-14	3.68E-14
CL2	3.07E-01	4.79E-01	6.25E-01	7.40E-01
NA2	1.81E-23	1.19E-23	9.37E-24	8.09E-24
O2-	9.01E-18	8.12E-18	7.65E-18	7.37E-18
O2	3.21E+18	4.81E+18	6.42E+18	8.02E+18
H2	1.46E+04	1.79E+04	2.06E+04	2.30E+04
OH-	3.03E-17	2.46E-17	2.16E-17	1.97E-17
OH	9.73E+08	1.32E+09	1.64E+09	1.93E+09
N2	1.20E+19	1.79E+19	2.39E+19	2.99E+19
NO	1.51E+12	2.27E+12	3.03E+12	3.78E+12
NH	2.27E-18	3.08E-18	3.82E-18	4.51E-18
NAOH	1.08E+09	1.19E+09	1.31E+09	1.43E+09
HOCL	3.37E+06	5.71E+06	8.09E+06	1.04E+07
CLO2	1.53E-03	2.87E-03	4.37E-03	5.95E-03
H2O	7.43E+20	1.12E+21	1.49E+21	1.86E+21
HO2	1.12E+07	1.67E+07	2.67E+07	3.53E+07
O3	1.42E+03	2.62E+03	4.03E+03	5.63E+03
NO2-	3.36E-08	3.71E-08	4.03E-08	4.35E-08
NO2	4.26E+12	7.82E+12	1.20E+13	1.68E+13
N2O	2.24E+08	4.11E+08	6.33E+08	8.48E+08
HNO	1.02E+01	1.69E+01	2.43E+01	3.21E+01
NO3-	1.13E-04	1.53E-04	1.92E-04	2.31E-04
NO3	2.21E+05	4.98E+05	8.85E+05	1.38E+06
N2O3	2.57E+01	7.08E+01	1.45E+02	2.58E+02
N2O4	5.05E+01	1.70E+02	4.04E+02	7.89E+02
N2O5	1.45E-02	6.01E-02	1.65E-01	3.59E-01
HNO2 (C)	1.09E+11	2.21E+11	3.66E+11	5.40E+11
HNO2 (T)	1.61E+11	3.27E+11	5.40E+11	7.99E+11
HNO3	7.67E+10	1.91E+11	3.65E+11	6.03E+11
NH3	2.47E+09	4.10E+09	5.88E+09	7.77E+09
NACL (C)	3.79E+17	5.66E+17	7.40E+17	9.03E+17
NAOH (C)	4.30E+09	6.25E+09	7.82E+09	9.07E+09
TOTAL	7.59E+20	1.14E+21	1.52E+21	1.90E+21

EQUILIBRIUM COMPOSITION FOR 0.98 WATER + 0.02 AIR + NACL (700°K)

CONCENTRATIONS IN PARTICLES/CM3

SPECIES	LOG10 OF DENSITY RATIO (STANDARD DENSITY = 1.1500E-01 GM/CM3)						
	-.70	-.52	-.40	-.30	-.22	-.15	-.10
E-	1.59E-16	9.45E-17	6.62E-17	5.06E-17	4.10E-17	3.44E-17	2.97E-17
NA	1.64E-01	1.31E-01	1.15E-01	1.05E-01	9.87E-02	9.49E-02	9.26E-02
NA+	4.64E-03	6.21E-03	7.74E-03	9.25E-03	1.08E-02	1.23E-02	1.39E-02
CL-	2.73E-07	2.07E-07	1.68E-07	1.42E-07	1.24E-07	1.09E-07	9.74E-08
CL	6.48E+03	8.23E+03	9.56E+03	1.06E+04	1.13E+04	1.19E+04	1.23E+04
H	4.90E-02	5.42E-02	5.83E-02	6.16E-02	6.45E-02	6.70E-02	6.93E-02
O-	1.06E-22	7.74E-23	6.26E-23	5.35E-23	4.74E-23	4.31E-23	3.98E-23
O	2.07E+03	2.53E+03	2.92E+03	3.27E+03	3.58E+03	3.86E+03	4.13E+03
N	7.34E-14	8.99E-14	1.04E-13	1.16E-13	1.27E-13	1.37E-13	1.47E-13
NACL	3.08E+14	5.85E+15	3.35E+16	7.74E+16	9.57E+16	8.46E+16	7.10E+16
NAO	2.25E-01	2.20E-01	2.22E-01	2.27E-01	2.34E-01	2.43E-01	2.53E-01
HCL	4.26E+10	5.98E+10	7.47E+10	8.74E+10	9.81E+10	1.07E+11	1.14E+11
NAH	4.00E-11	3.53E-11	3.31E-11	3.20E-11	3.16E-11	3.16E-11	3.16E-11
CL2	9.24E+00	1.49E+01	2.01E+01	2.46E+01	2.83E+01	3.12E+01	3.33E+01
NA2	1.42E-19	9.07E-20	6.90E-20	5.77E-20	5.12E-20	4.73E-20	4.51E-20
O2-	1.30E-14	1.16E-14	1.08E-14	1.04E-14	1.01E-14	9.87E-15	9.75E-15
O2	3.21E+18	4.81E+18	6.42E+18	8.02E+18	9.63E+18	1.12E+19	1.28E+19
H2	3.60E+05	4.41E+05	5.09E+05	5.69E+05	6.24E+05	6.74E+05	7.20E+05
OH-	6.00E-14	4.85E-14	4.21E-14	3.81E-14	3.53E-14	3.33E-14	3.19E-14
OH	8.13E+09	1.10E+10	1.37E+10	1.62E+10	1.85E+10	2.08E+10	2.30E+10
N2	1.20E+19	1.79E+19	2.39E+19	2.99E+19	3.59E+19	4.19E+19	4.78E+19
NO	5.01E+12	7.51E+12	1.00E+13	1.25E+13	1.50E+13	1.75E+13	2.00E+13
NH	1.65E-15	2.24E-15	2.78E-15	3.28E-15	3.76E-15	4.22E-15	4.67E-15
NAOH	1.47E+10	1.59E+10	1.72E+10	1.86E+10	2.01E+10	2.17E+10	2.34E+10
HOCL	2.78E+07	4.79E+07	6.90E+07	9.03E+07	1.11E+08	1.31E+08	1.49E+08
CLO2	3.46E-02	6.60E-02	1.02E-01	1.41E-01	1.82E-01	2.23E-01	2.63E-01
H2O	7.43E+20	1.12E+21	1.49E+21	1.86E+21	2.23E+21	2.60E+21	2.97E+21
HO2	7.41E+07	1.23E+08	1.76E+08	2.33E+08	2.92E+08	3.55E+08	4.19E+08
O3	9.72E+03	1.79E+04	2.75E+04	3.84E+04	5.05E+04	6.37E+04	7.78E+04
NO2-	5.60E-06	6.13E-06	6.61E-06	7.06E-06	7.51E-06	7.96E-06	8.40E-06
NO2	6.74E+12	1.24E+13	1.91E+13	2.67E+13	3.50E+13	4.42E+13	5.39E+13
N2O	6.82E+08	1.25E+09	1.93E+09	2.70E+09	3.54E+09	4.47E+09	5.46E+09
HNO	1.90E+02	3.10E+02	4.52E+02	5.98E+02	7.51E+02	9.11E+02	1.08E+03
NO3-	4.63E-03	6.21E-03	7.73E-03	9.20E-03	1.08E-02	1.23E-02	1.39E-02
NO3	5.38E+05	1.21E+06	2.15E+06	3.36E+06	4.84E+06	6.59E+06	8.61E+06
N2O3	8.62E+01	2.38E+02	4.88E+02	8.52E+02	1.34E+03	1.98E+03	2.76E+03
N2O4	6.71E+01	2.26E+02	5.37E+02	1.05E+03	1.81E+03	2.88E+03	4.29E+03
N2O5	2.22E-02	9.19E-02	2.52E-01	5.49E-01	1.04E+00	1.78E+00	2.65E+00
HNO2 (C)	2.05E+11	4.17E+11	6.91E+11	1.02E+12	1.40E+12	1.84E+12	2.32E+12
HNO2 (T)	2.96E+11	6.02E+11	9.96E+11	1.47E+12	2.02E+12	2.65E+12	3.35E+12
HNO3	6.97E+10	1.74E+11	3.31E+11	5.48E+11	8.25E+11	1.17E+12	1.58E+12
NH3	1.53E+10	2.54E+10	3.63E+10	4.80E+10	6.03E+10	7.32E+10	8.64E+10
NACL (C)	3.79E+17	5.63E+17	7.25E+17	8.71E+17	1.04E+18	1.24E+18	1.45E+18
NAOH (C)	2.79E+10	4.40E+10	5.75E+10	6.89E+10	7.81E+10	8.55E+10	9.11E+10
TOTAL	7.59E+20	1.14E+21	1.52E+21	1.90E+21	2.28E+21	2.65E+21	3.03E+21

EQUILIBRIUM COMPOSITION FOR 0.98 WATER + 0.02 AIR + NACL (750^{o}K)

CONCENTRATIONS IN PARTICLES/CM3

SPECIES	LOG10 OF DENSITY RATIO (STANDARD DENSITY = 1.1500E-01 GM/CM3)								
	-.70	-.52	-.40	-.30	-.22	-.15	-.10	-.05	-.00
E-	1.51E-13	8.95E-14	6.23E-14	4.74E-14	3.81E-14	3.18E-14	2.74E-14	2.40E-14	2.14E-14
NA	1.20E+01	9.44E+00	8.13E+00	7.35E+00	6.84E+00	6.50E+00	6.27E+00	6.11E+00	6.01E+00
NA+	1.15E-01	1.53E-01	1.89E-01	2.25E-01	2.61E-01	2.96E-01	3.33E-01	3.69E-01	4.07E-01
CL-	7.47E-05	5.69E-05	4.66E-05	3.98E-05	3.48E-05	3.09E-05	2.78E-05	2.53E-05	2.31E-05
CL	1.13E+05	1.45E+05	1.71E+05	1.92E+05	2.08E+05	2.22E+05	2.32E+05	2.40E+05	2.46E+05
H	2.38E+00	2.63E+00	2.83E+00	2.99E+00	3.13E+00	3.26E+00	3.37E+00	3.47E+00	3.56E+00
O-	3.07E-19	2.22E-19	1.79E-19	1.52E-19	1.34E-19	1.21E-19	1.11E-19	1.03E-19	9.73E-20
O	3.56E+04	4.36E+04	5.04E+04	5.63E+04	6.17E+04	6.66E+04	7.12E+04	7.55E+04	7.96E+04
N	1.64E-11	2.01E-11	2.32E-11	2.59E-11	2.84E-11	3.07E-11	3.28E-11	3.48E-11	3.67E-11
NACL	9.22E+14	1.20E+16	5.53E+16	1.16E+17	1.43E+17	1.32E+17	1.17E+17	1.29E+17	2.24E+17
NAO	1.29E+01	1.24E+01	1.24E+01	1.25E+01	1.27E+01	1.31E+01	1.35E+01	1.39E+01	1.45E+01
HCL	2.57E+11	3.65E+11	4.63E+11	5.49E+11	6.24E+11	6.90E+11	7.47E+11	7.96E+11	8.38E+11
NAH	1.45E-08	1.26E-08	1.17E-08	1.12E-08	1.09E-08	1.07E-08	1.07E-08	1.08E-08	1.09E-08
CL2	1.78E+02	2.95E+02	4.09E+02	5.10E+02	6.07E+02	6.87E+02	7.53E+02	8.06E+02	8.46E+02
NA2	3.25E-16	2.02E-16	1.50E-16	1.23E-16	1.06E-16	9.59E-17	8.92E-17	8.48E-17	8.21E-17
O2-	7.00E-12	6.22E-12	5.78E-12	5.49E-12	5.30E-12	5.17E-12	5.07E-12	5.01E-12	4.97E-12
O2	3.21E+18	4.81E+18	6.42E+18	8.02E+18	9.63E+18	1.12E+19	1.28E+19	1.44E+19	1.60E+19
H2	5.81E+06	7.12E+06	8.22E+06	9.19E+06	1.01E+07	1.09E+07	1.16E+07	1.23E+07	1.30E+07
OH-	4.26E-11	3.42E-11	2.96E-11	2.66E-11	2.45E-11	2.30E-11	2.18E-11	2.09E-11	2.02E-11
OH	5.12E+10	6.95E+10	8.62E+10	1.02E+11	1.17E+11	1.31E+11	1.45E+11	1.56E+11	1.71E+11
N2	1.20E+19	1.79E+19	2.39E+19	2.99E+19	3.59E+19	4.19E+19	4.78E+19	5.38E+19	5.98E+19
NO	1.41E+13	2.12E+13	2.82E+13	3.53E+13	4.23E+13	4.94E+13	5.65E+13	6.35E+13	7.06E+13
NH	4.99E-13	6.76E-13	8.39E-13	9.92E-13	1.14E-12	1.28E-12	1.41E-12	1.54E-12	1.67E-12
NAOH	1.39E+11	1.49E+11	1.59E+11	1.70E+11	1.82E+11	1.94E+11	2.07E+11	2.20E+11	2.34E+11
HOCL	1.74E+08	3.04E+08	4.44E+08	5.88E+08	7.33E+08	8.76E+08	1.01E+09	1.15E+09	1.27E+09
CLO2	5.21E-01	1.00E+00	1.58E+00	2.21E+00	2.88E+00	3.58E+00	4.28E+00	4.98E+00	5.67E+00
H2O	7.43E+20	1.12E+21	1.49E+21	1.86E+21	2.23E+21	2.60E+21	2.97E+21	3.35E+21	3.72E+21
HO2	3.80E+08	6.31E+08	9.04E+08	1.19E+09	1.50E+09	1.82E+09	2.15E+09	2.49E+09	2.84E+09
O3	5.16E+04	9.47E+04	1.46E+05	2.04E+05	2.68E+05	3.38E+05	4.13E+05	4.92E+05	5.77E+05
NO2-	4.65E-04	5.06E-04	5.43E-04	5.77E-04	6.10E-04	6.42E-04	6.74E-04	7.06E-04	7.39E-04
NO2	1.01E+13	1.85E+13	2.85E+13	3.98E+13	5.23E+13	6.59E+13	8.05E+13	9.61E+13	1.13E+14
N2O	1.80E+09	3.31E+09	5.09E+09	7.12E+09	9.36E+09	1.18E+10	1.44E+10	1.72E+10	2.01E+10
HNO	2.41E+03	3.99E+03	5.72E+03	7.56E+03	9.50E+03	1.15E+04	1.36E+04	1.58E+04	1.80E+04
NO3-	1.14E-01	1.53E-01	1.89E-01	2.24E-01	2.60E-01	2.96E-01	3.32E-01	3.69E-01	4.06E-01
NO3	1.17E+06	2.63E+06	4.68E+06	7.32E+06	1.05E+07	1.43E+07	1.87E+07	2.37E+07	2.93E+07
N2O3	2.49E+02	6.86E+02	1.41E+03	2.46E+03	3.88E+03	5.70E+03	7.96E+03	1.07E+04	1.39E+04
N2O4	8.73E+01	2.95E+02	6.99E+02	1.36E+03	2.36E+03	3.74E+03	5.59E+03	7.96E+03	1.09E+04
N2O5	3.27E-02	1.35E-01	3.70E-01	8.08E-01	1.53E+00	2.62E+00	4.19E+00	6.32E+00	9.14E+00
HNO2 (C)	3.59E+11	7.29E+11	1.21E+12	1.78E+12	2.45E+12	3.21E+12	4.06E+12	4.98E+12	5.99E+12
HNO2 (T)	5.06E+11	1.03E+12	1.70E+12	2.52E+12	3.46E+12	4.53E+12	5.73E+12	7.04E+12	8.46E+12
HNO3	6.47E+10	1.61E+11	3.08E+11	5.09E+11	7.67E+11	1.08E+12	1.46E+12	1.91E+12	2.42E+12
NH3	7.42E+10	1.23E+11	1.77E+11	2.33E+11	2.93E+11	3.55E+11	4.20E+11	4.87E+11	5.55E+11
NACL (C)	3.78E+17	5.57E+17	7.03E+17	8.32E+17	9.95E+17	1.20E+18	1.40E+18	1.5[illegible]E+18	1.67E+18
NAOH (C)	1.18E+11	2.17E+11	3.04E+11	3.79E+11	4.43E+11	4.97E+11	5.42E+11	5.77E+11	6.05E+11
TOTAL	7.59E+20	1.14E+21	1.52E+21	1.90E+21	2.28E+21	2.65E+21	3.03E+21	3.41E+21	3.79E+21

EQUILIBRIUM COMPOSITION FOR 0.98 WATER + 0.02 AIR + NACL (800°K)

CONCENTRATIONS IN PARTICLES/CM3

SPECIES LOG10 OF DENSITY RATIO (STANDARD DENSITY = 1.1500E-01 GM/CM3)

SPECIES	-.70	-.52	-.40	-.30	-.22	-.15	-.10	-.05	0.00	.04
E-	6.00E-11	3.54E-11	2.46E-11	1.86E-11	1.49E-11	1.24E-11	1.06E-11	9.28E-12	8.25E-12	7.43E-12
NA	4.93E+02	3.86E+02	3.29E+02	2.95E+02	2.72E+02	2.56E+02	2.45E+02	2.36E+02	2.30E+02	2.26E+02
NA+	1.89E+00	2.51E+00	3.08E+00	3.64E+00	4.20E+00	4.75E+00	5.31E+00	5.87E+00	6.43E+00	7.01E+00
CL-	1.00E-02	7.68E-03	6.33E-03	5.47E-03	4.78E-03	4.27E-03	3.87E-03	3.53E-03	3.25E-03	3.01E-03
CL	1.39E+06	1.81E+06	2.15E+06	2.44E+06	2.68E+06	2.88E+06	3.04E+06	3.18E+06	3.29E+06	3.38E+06
H	7.13E+01	7.89E+01	8.48E+01	8.97E+01	9.30E+01	9.75E+01	1.01E+02	1.04E+02	1.07E+02	1.09E+02
O-	3.20E-16	2.31E-16	1.85E-16	1.57E-16	1.38E-16	1.24E-16	1.13E-16	1.05E-16	9.82E-17	9.28E-17
O	4.30E+05	5.27E+05	6.08E+05	6.80E+05	7.45E+05	8.05E+05	8.60E+05	9.13E+05	9.62E+05	1.01E+06
N	1.86E-09	2.28E-09	2.64E-09	2.95E-09	3.23E-09	3.44E-09	3.73E-09	3.95E-09	4.17E-09	4.37E-09
NACL	2.06E+15	1.88E+16	7.19E+16	1.42E+17	1.78E+17	1.75E+17	1.67E+17	1.90E+17	3.20E+17	9.79E+17
NAO	4.30E+02	4.12E+02	4.06E+02	4.06E+02	4.11E+02	4.18E+02	4.27E+02	4.37E+02	4.50E+02	4.63E+02
HCL	1.26E+12	1.81E+12	2.31E+12	2.76E+12	3.17E+12	3.55E+12	3.88E+12	4.17E+12	4.44E+12	4.67E+12
NAH	2.43E-06	2.10E-06	1.93E-06	1.82E-06	1.76E-06	1.72E-06	1.70E-06	1.70E-06	1.70E-06	1.71E-06
CL2	2.44E+03	4.12E+03	5.82E+03	7.47E+03	9.00E+03	1.04E+04	1.16E+04	1.27E+04	1.36E+04	1.44E+04
NA2	2.66E-13	1.62E-13	1.18E-13	9.48E-14	8.06E-14	7.15E-14	6.53E-14	6.10E-14	5.80E-14	5.59E-14
O2-	1.68E-09	1.49E-09	1.38E-09	1.30E-09	1.25E-09	1.22E-09	1.19E-09	1.17E-09	1.15E-09	1.14E-09
O2	3.21E+18	4.81E+18	6.42E+18	8.02E+18	9.63E+18	1.12E+19	1.28E+19	1.44E+19	1.60E+19	1.76E+19
H2	6.64E+07	8.14E+07	9.39E+07	1.05E+08	1.15E+08	1.24E+08	1.33E+08	1.41E+08	1.49E+08	1.56E+08
OH-	1.30E-08	1.04E-08	8.97E-09	8.03E-09	7.37E-09	6.89E-09	6.51E-09	6.22E-09	5.98E-09	5.79E-09
OH	2.56E+11	3.48E+11	4.31E+11	5.10E+11	5.85E+11	6.56E+11	7.25E+11	7.92E+11	8.58E+11	9.21E+11
N2	1.20E+19	1.79E+19	2.39E+19	2.99E+19	3.59E+19	4.19E+19	4.78E+19	5.38E+19	5.98E+19	6.58E+19
NO	3.50E+13	5.25E+13	6.99E+13	8.74E+13	1.05E+14	1.22E+14	1.40E+14	1.57E+14	1.75E+14	1.92E+14
NH	7.39E-11	1.00E-10	1.24E-10	1.47E-10	1.68E-10	1.89E-10	2.09E-10	2.28E-10	2.47E-10	2.65E-10
NAOH	9.73E+11	1.03E+12	1.09E+12	1.15E+12	1.22E+12	1.29E+12	1.36E+12	1.44E+12	1.52E+12	1.60E+12
HOCL	8.82E+08	1.55E+09	2.29E+09	3.06E+09	3.86E+09	4.65E+09	5.44E+09	6.21E+09	6.96E+09	7.68E+09
CLO2	5.67E+00	1.10E+01	1.75E+01	2.48E+01	3.27E+01	4.10E+01	4.95E+01	5.82E+01	6.70E+01	7.57E+01
H2O	7.43E+20	1.12E+21	1.49E+21	1.86E+21	2.23E+21	2.60E+21	2.97E+21	3.35E+21	3.72E+21	4.09E+21
HO2	1.59E+09	2.64E+09	3.79E+09	5.00E+09	6.28E+09	7.62E+09	9.00E+09	1.04E+10	1.19E+10	1.34E+10
O3	2.23E+05	4.09E+05	6.30E+05	8.81E+05	1.16E+06	1.46E+06	1.78E+06	2.13E+06	2.49E+06	2.87E+06
NO2-	2.18E-02	2.37E-02	2.55E-02	2.67E-02	2.81E-02	2.95E-02	3.09E-02	3.22E-02	3.35E-02	3.48E-02
NO2	1.43E+13	2.63E+13	4.05E+13	5.66E+13	7.44E+13	9.38E+13	1.15E+14	1.37E+14	1.60E+14	1.85E+14
N2O	4.23E+09	7.76E+09	1.20E+10	1.67E+10	2.20E+10	2.77E+10	3.38E+10	4.03E+10	4.73E+10	5.45E+10
HNO	2.22E+04	3.68E+04	5.28E+04	6.98E+04	8.76E+04	1.06E+05	1.26E+05	1.45E+05	1.66E+05	1.87E+05
NO3-	1.86E+00	2.47E+00	3.05E+00	3.61E+00	4.16E+00	4.72E+00	5.27E+00	5.83E+00	6.40E+00	6.98E+00
NO3	2.33E+06	5.24E+06	9.31E+06	1.46E+07	2.10E+07	2.85E+07	3.73E+07	4.72E+07	5.82E+07	7.04E+07
N2O3	6.35E+02	1.75E+03	3.59E+03	6.28E+03	9.90E+03	1.46E+04	2.03E+04	2.73E+04	3.55E+04	4.51E+04
N2O4	1.12E+02	3.77E+02	8.93E+02	1.74E+03	3.01E+03	4.79E+03	7.14E+03	1.02E+04	1.40E+04	1.86E+04
N2O5	4.66E-02	1.93E-01	5.27E-01	1.15E+00	2.18E+00	3.74E+00	5.96E+00	9.00E+00	1.30E+01	1.82E+01
HNO2 (C)	5.87E+11	1.19E+12	1.97E+12	2.92E+12	4.01E+12	5.26E+12	6.64E+12	8.16E+12	9.81E+12	1.16E+13
HNO2 (T)	8.13E+11	1.65E+12	2.74E+12	4.04E+12	5.56E+12	7.28E+12	9.20E+12	1.13E+13	1.36E+13	1.61E+13
HNO3	6.12E+10	1.52E+11	2.91E+11	4.81E+11	7.25E+11	1.03E+12	1.34E+12	1.81E+12	2.29E+12	2.84E+12
NH3	2.96E+11	4.92E+11	7.05E+11	9.32E+11	1.17E+12	1.42E+12	1.68E+12	1.94E+12	2.22E+12	2.50E+12
NACL (C)	3.77E+17	5.50E+17	6.87E+17	8.07E+17	9.60E+17	1.15E+18	1.35E+18	1.52E+18	1.58E+18	1.11E+18
NAOH (C)	2.65E+11	7.77E+11	1.22E+12	1.61E+12	1.96E+12	2.26E+12	2.52E+12	2.74E+12	2.93E+12	3.07E+12
TOTAL	7.59E+20	1.14E+21	1.52E+21	1.90E+21	2.28E+21	2.65E+21	3.03E+21	3.41E+21	3.79E+21	4.17E+21

EQUILIBRIUM COMPOSITION FOR 0.98 WATER + 0.02 AIR + NACL (850°K)

CONCENTRATIONS IN PARTICLES/CM3

SPECIES	LOG10 OF DENSITY RATIO (STANDARD DENSITY = 1.1500E-01 GM/CM3)									
	-.70	-.52	-.40	-.30	-.22	-.15	-.10	-.05	-.00	.04
E-	1.14E-08	6.85E-09	4.75E-09	3.59E-09	2.87E-09	2.38E-09	2.03E-09	1.77E-09	1.57E-09	1.41E-09
NA	1.27E+04	1.01E+04	8.54E+03	7.59E+03	6.95E+03	6.49E+03	6.16E+03	5.92E+03	5.73E+03	5.59E+03
NA+	2.29E+01	2.90E+01	3.64E+01	4.27E+01	4.90E+01	5.52E+01	6.14E+01	6.76E+01	7.39E+01	8.02E+01
CL-	7.44E-01	5.70E-01	4.74E-01	4.09E-01	3.62E-01	3.25E-01	2.96E-01	2.72E-01	2.51E-01	2.34E-01
CL	1.31E+07	1.68E+07	2.01E+07	2.29E+07	2.54E+07	2.75E+07	2.93E+07	3.09E+07	3.23E+07	3.34E+07
H	1.43E+03	1.59E+03	1.71E+03	1.80E+03	1.89E+03	1.96E+03	2.03E+03	2.09E+03	2.14E+03	2.20E+03
O-	1.42E-13	1.04E-13	8.34E-14	7.06E-14	6.17E-14	5.53E-14	5.05E-14	4.67E-14	4.36E-14	4.11E-14
O	3.84E+06	4.75E+06	5.48E+06	6.13E+06	6.72E+06	7.25E+06	7.75E+06	8.22E+06	8.67E+06	9.09E+06
N	1.21E-07	1.49E-07	1.72E-07	1.92E-07	2.10E-07	2.27E-07	2.43E-07	2.58E-07	2.72E-07	2.85E-07
NACL	4.17E+15	2.76E+16	8.80E+16	1.61E+17	2.01E+17	2.06E+17	2.06E+17	2.42E+17	3.97E+17	1.09E+18
NAO	9.21E+03	8.98E+03	8.78E+03	8.72E+03	8.75E+03	8.84E+03	8.96E+03	9.13E+03	9.32E+03	9.53E+03
HCL	5.23E+12	7.38E+12	9.50E+12	1.15E+13	1.33E+13	1.50E+13	1.65E+13	1.79E+13	1.92E+13	2.03E+13
NAH	2.16E-04	1.90E-04	1.73E-04	1.63E-04	1.56E-04	1.52E-04	1.49E-04	1.47E-04	1.46E-04	1.46E-04
CL2	2.59E+04	4.22E+04	6.05E+04	7.80E+04	9.66E+04	1.13E+05	1.29E+05	1.43E+05	1.56E+05	1.67E+05
NA2	9.20E-11	5.83E-11	4.18E-11	3.30E-11	2.77E-11	2.42E-11	2.18E-11	2.01E-11	1.88E-11	1.79E-11
O2-	2.04E-07	1.83E-07	1.70E-07	1.60E-07	1.54E-07	1.49E-07	1.45E-07	1.42E-07	1.40E-07	1.39E-07
O2	3.21E+18	4.81E+18	6.47E+18	8.02E+18	9.63E+18	1.12E+19	1.28E+19	1.44E+19	1.60E+19	1.76E+19
H2	5.71E+08	6.99E+08	8.07E+08	9.03E+08	9.89E+08	1.07E+09	1.14E+09	1.21E+09	1.28E+09	1.34E+09
OH-	1.95E-06	1.59E-06	1.37E-06	1.22E-06	1.12E-06	1.04E-06	9.83E-07	9.36E-07	8.98E-07	8.66E-07
OH	1.06E+12	1.44E+12	1.79E+12	2.11E+12	2.42E+12	2.72E+12	3.00E+12	3.28E+12	3.55E+12	3.82E+12
N2	1.20E+19	1.79E+19	2.39E+19	2.99E+19	3.59E+19	4.19E+19	4.78E+19	5.38E+19	5.98E+19	6.58E+19
NO	7.79E+13	1.17E+14	1.56E+14	1.95E+14	2.34E+14	2.73E+14	3.11E+14	3.50E+14	3.89E+14	4.28E+14
N+	6.08E-09	8.24E-09	1.02E-08	1.21E-08	1.39E-08	1.56E-08	1.72E-08	1.88E-08	2.03E-08	2.18E-08
NAOH	5.23E+12	5.64E+12	5.93E+12	6.23E+12	6.54E+12	6.86E+12	7.20E+12	7.55E+12	7.91E+12	8.29E+12
HOCL	3.78E+09	6.54E+09	9.73E+09	1.31E+10	1.67E+10	2.03E+10	2.39E+10	2.75E+10	3.11E+10	3.45E+10
CLO2	4.80E+01	9.18E+01	1.47E+02	2.09E+02	2.78E+02	3.51E+02	4.28E+02	5.08E+02	5.89E+02	6.71E+02
H2O	7.43E+20	1.12E+21	1.49E+21	1.86E+21	2.23E+21	2.60E+21	2.97E+21	3.35E+21	3.72E+21	4.09E+21
HO2	5.64E+09	9.36E+09	1.34E+10	1.77E+10	2.23E+10	2.70E+10	3.19E+10	3.69E+10	4.21E+10	4.75E+10
O3	8.12E+05	1.49E+06	2.30E+06	3.21E+06	4.22E+06	5.32E+06	6.50E+06	7.76E+06	9.08E+06	1.05E+07
NO2-	6.26E-01	6.91E-01	7.38E-01	7.80E-01	8.19E-01	8.57E-01	8.93E-01	9.29E-01	9.64E-01	9.99E-01
NO2	1.96E+13	3.60E+13	5.54E+13	7.75E+13	1.02E+14	1.28E+14	1.57E+14	1.87E+14	2.19E+14	2.53E+14
N2O	9.00E+09	1.65E+10	2.55E+10	3.56E+10	4.68E+10	5.90E+10	7.20E+10	8.60E+10	1.01E+11	1.16E+11
HNO	1.58E+05	2.62E+05	3.76E+05	4.97E+05	6.24E+05	7.56E+05	8.93E+05	1.04E+06	1.18E+06	1.33E+06
NO3-	2.11E+01	2.85E+01	3.52E+01	4.16E+01	4.78E+01	5.40E+01	6.02E+01	6.64E+01	7.27E+01	7.90E+01
NO3	4.34E+06	9.68E+06	1.72E+07	2.69E+07	3.87E+07	5.27E+07	6.88E+07	8.71E+07	1.08E+08	1.30E+08
N2O3	1.47E+03	4.04E+03	8.24E+03	1.45E+04	2.28E+04	3.36E+04	4.69E+04	6.29E+04	8.19E+04	1.04E+05
N2O4	1.41E+02	4.74E+02	1.12E+03	2.20E+03	3.79E+03	6.03E+03	8.99E+03	1.28E+04	1.76E+04	2.34E+04
N2O5	6.46E-02	2.67E-01	7.31E-01	1.60E+00	3.02E+00	5.18E+00	8.27E+00	1.25E+01	1.81E+01	2.52E+01
HNO2 (C)	9.12E+11	1.85E+12	3.07E+12	4.53E+12	6.23E+12	8.16E+12	1.03E+13	1.27E+13	1.52E+13	1.80E+13
HNO2 (T)	1.24E+12	2.53E+12	4.18E+12	6.18E+12	8.50E+12	1.11E+13	1.41E+13	1.73E+13	2.08E+13	2.45E+13
HNO3	5.88E+10	1.46E+11	2.80E+11	4.62E+11	6.96E+11	9.85E+11	1.33E+12	1.73E+12	2.20E+12	2.72E+12
NH3	1.01E+12	1.67E+12	2.40E+12	3.17E+12	3.98E+12	4.82E+12	5.70E+12	6.61E+12	7.53E+12	8.49E+12
NACL (C)	3.75E+17	5.41E+17	6.70E+17	7.87E+17	9.37E+17	1.12E+18	1.31E+18	1.46E+18	1.50E+18	9.99E+17
NAOH (C)	0.	1.74E+12	3.58E+12	5.25E+12	6.76E+12	8.11E+12	9.31E+12	1.04E+13	1.13E+13	1.21E+13
TOTAL	7.59E+20	1.14E+21	1.52E+21	1.90E+21	2.28E+21	2.65E+21	3.03E+21	3.41E+21	3.79E+21	4.17E+21

EQUILIBRIUM COMPOSITION FOR 0.98 WATER + 0.02 AIR + NACL (9000°K)

CONCENTRATIONS IN PARTICLES/CM3

SPECIES	LOG10 OF DENSITY RATIO (STANDARD DENSITY = 1.1500E-01 GM/CM3)							
	-.70	-.52	-.40	-.30	-.22	-.15	-.10	-.05
E-	1.06E-06	7.01E-07	4.91E-07	3.73E-07	2.99E-07	2.48E-07	2.12E-07	1.85E-07
NA	2.00E+05	1.78E+05	1.50E+05	1.33E+05	1.21E+05	1.12E+05	1.06E+05	1.01E+05
NA+	2.05E+02	2.77E+02	3.32E+02	3.86E+02	4.39E+02	4.91E+02	5.43E+02	5.96E+02
CL-	3.33E+01	2.50E+01	2.12E+01	1.85E+01	1.65E+01	1.49E+01	1.37E+01	1.26E+01
CL	1.08E+08	1.23E+08	1.48E+08	1.70E+08	1.89E+08	2.06E+08	2.21E+08	2.35E+08
H	2.07E+04	2.29E+04	2.46E+04	2.60E+04	2.72E+04	2.83E+04	2.93E+04	3.01E+04
O-	2.78E-11	2.25E-11	1.82E-11	1.55E-11	1.36E-11	1.22E-11	1.11E-11	1.03E-11
O	2.74E+07	3.35E+07	3.87E+07	4.31E+07	4.74E+07	5.12E+07	5.47E+07	5.80E+07
N	4.98E-06	6.10E-06	7.04E-06	7.87E-06	8.62E-06	9.31E-06	9.95E-06	1.06E-05
NACL	7.74E+15	3.91E+16	1.08E+17	1.92E+17	2.53E+17	2.90E+17	3.37E+17	4.63E+17
NAO	1.24E+05	1.35E+05	1.31E+05	1.30E+05	1.30E+05	1.30E+05	1.31E+05	1.33E+05
HCL	2.06E+13	2.60E+13	3.37E+13	4.10E+13	4.77E+13	5.41E+13	6.00E+13	6.56E+13
NAH	1.03E-02	1.02E-02	9.22E-03	8.62E-03	8.21E-03	7.93E-03	7.74E-03	7.61E-03
CL2	2.62E+05	3.40E+05	4.94E+05	6.52E+05	8.09E+05	9.61E+05	1.11E+06	1.25E+06
NA2	1.30E-08	1.03E-08	7.32E-09	5.71E-09	4.74E-09	4.10E-09	3.65E-09	3.32E-09
O2-	1.27E-05	1.25E-05	1.17E-05	1.11E-05	1.07E-05	1.04E-05	1.01E-05	9.91E-06
O2	3.21E+18	4.91E+18	6.42E+18	8.02E+18	9.63E+18	1.12E+19	1.28E+19	1.44E+19
H2	3.87E+09	4.74E+09	5.47E+09	6.12E+09	6.70E+09	7.24E+09	7.74E+09	8.21E+09
OH-	1.46E-04	1.31E-04	1.19E-04	1.02E-04	9.39E-05	8.75E-05	8.26E-05	7.86E-05
OH	3.76E+12	5.09E+12	6.52E+12	7.47E+12	8.56E+12	9.61E+12	1.06E+13	1.16E+13
N2	1.20E+19	1.79E+19	2.39E+19	2.99E+19	3.59E+19	4.19E+19	4.78E+19	5.38E+19
NO	1.59E+14	2.38E+14	3.17E+14	3.97E+14	4.76E+14	5.55E+14	6.34E+14	7.14E+14
NH	3.07E-07	4.16E-07	5.16E-07	6.10E-07	7.00E-07	7.85E-07	8.68E-07	9.48E-07
NAOH	2.07E+13	2.50E+13	2.61E+13	2.73E+13	2.85E+13	2.97E+13	3.10E+13	3.23E+13
HOCL	1.54E+10	2.38E+10	3.56E+10	4.83E+10	6.17E+10	7.55E+10	8.95E+10	1.04E+11
CLO2	3.57E+02	6.31E+02	9.82E+02	1.41E+03	1.88E+03	2.40E+03	2.94E+03	3.51E+03
H2O	7.43E+20	1.12E+21	1.49E+21	1.86E+21	2.23E+21	2.60E+21	2.97E+21	3.35E+21
HO2	1.74E+10	2.88E+10	4.13E+10	5.46E+10	6.86E+10	8.31E+10	9.82E+10	1.14E+11
O3	2.57E+06	4.73E+06	7.28E+06	1.02E+07	1.34E+07	1.69E+07	2.06E+07	2.46E+07
NO2-	1.09E+01	1.32E+01	1.42E+01	1.51E+01	1.59E+01	1.66E+01	1.73E+01	1.80E+01
NO2	2.59E+13	4.77E+13	7.34E+13	1.03E+14	1.35E+14	1.70E+14	2.08E+14	2.48E+14
N2O	1.77E+10	3.25E+10	5.01E+10	7.00E+10	9.20E+10	1.16E+11	1.42E+11	1.69E+11
HNO	9.05E+05	1.50E+06	2.15E+06	2.85E+06	3.57E+06	4.33E+06	5.12E+06	5.93E+06
NO3-	1.60E+02	2.38E+02	2.97E+02	3.53E+02	4.07E+02	4.60E+02	5.12E+02	5.65E+02
NO3	7.47E+06	1.68E+07	2.97E+07	4.67E+07	6.72E+07	9.15E+07	1.19E+08	1.51E+08
N2O3	3.11E+03	8.56E+03	1.76E+04	3.07E+04	4.84E+04	7.12E+04	9.94E+04	1.33E+05
N2O4	1.75E+02	5.89E+02	1.40E+03	2.73E+03	4.72E+03	7.49E+03	1.12E+04	1.59E+04
N2O5	8.76E-02	3.62E-01	9.91E-01	2.16E+00	4.10E+00	7.02E+00	1.12E+01	1.69E+01
HNO2 (C)	1.35E+12	2.75E+12	4.56E+12	6.73E+12	9.26E+12	1.21E+13	1.53E+13	1.88E+13
HNO2 (T)	1.82E+12	3.70E+12	6.12E+12	9.05E+12	1.24E+13	1.63E+13	2.06E+13	2.53E+13
HNO3	5.71E+10	1.42E+11	2.71E+11	4.49E+11	6.76E+11	9.56E+11	1.29E+12	1.68E+12
NH3	3.00E+12	4.97E+12	7.13E+12	9.42E+12	1.18E+13	1.43E+13	1.69E+13	1.96E+13
NACL (C)	3.71E+17	5.30E+17	6.50E+17	7.56E+17	8.85E+17	1.04E+18	1.18E+18	1.24E+18
NAOH (C)		1.07E+12	7.66E+12	1.37E+13	1.93E+13	2.45E+13	2.91E+13	3.34E+13
TOTAL	7.59E+20	1.14E+21	1.52E+21	1.90E+21	2.28E+21	2.66E+21	3.03E+21	3.41E+21

EQUILIBRIUM COMPOSITION FOR 0.98 WATER + 0.02 AIR + NACL (950°K)

CONCENTRATIONS IN PARTICLES/CM3

SPECIES	LOG10 OF DENSITY RATIO (STANDARD DENSITY = 1.1500E-01 GM/CM3)					
	-.70	-.52	-.40	-.30	-.22	-.15
E-	5.12E-05	3.76E-05	2.86E-05	2.22E-05	1.80E-05	1.51E-05
NA	2.35E+06	2.14E+06	1.93E+06	1.70E+06	1.54E+06	1.42E+06
NA+	1.77E+03	2.19E+03	2.60E+03	2.95E+03	3.29E+03	3.63E+03
CL-	8.29E+02	6.78E+02	5.80E+02	5.20E+02	4.72E+02	4.34E+02
CL	7.04E+08	7.86E+08	8.82E+08	1.02E+09	1.14E+09	1.25E+09
H	2.26E+05	2.50E+05	2.68E+05	2.84E+05	2.97E+05	3.09E+05
O-	2.61E-09	2.34E-09	2.06E-09	1.79E-09	1.59E-09	1.40E-09
O	1.57E+08	1.93E+08	2.22E+08	2.49E+08	2.72E+08	2.94E+08
N	1.38E-04	1.69E-04	1.95E-04	2.18E-04	2.39E-04	2.58E-04
NACL	2.00E+16	1.07E+17	3.59E+17	8.28E+17	1.43E+18	2.04E+18
NAO	1.26E+06	1.41E+06	1.47E+06	1.44E+06	1.43E+06	1.43E+06
HCL	7.05E+13	8.70E+13	1.05E+14	1.28E+14	1.50E+14	1.72E+14
NAH	3.27E-01	3.30E-01	3.21E-01	2.98E-01	2.82E-01	2.71E-01
CL2	2.07E+06	2.58E+06	3.25E+06	4.34E+06	5.45E+06	6.56E+06
NA2	1.08E-06	8.93E-07	7.32E-07	5.68E-07	4.63E-07	3.95E-07
O2-	4.24E-04	4.67E-04	4.79E-04	4.60E-04	4.48E-04	4.37E-04
O2	3.21E+18	4.81E+18	6.42E+18	8.02E+18	9.62E+18	1.12E+19
H2	2.15E+10	2.63E+10	3.03E+10	3.39E+10	3.72E+10	4.01E+10
OH-	5.78E-03	5.75E-03	5.44E-03	4.99E-03	4.64E-03	4.36E-03
OH	1.18E+13	1.58E+13	1.96E+13	2.31E+13	2.65E+13	2.98E+13
N2	1.20E+19	1.79E+19	2.39E+19	2.99E+19	3.59E+19	4.19E+19
NO	3.00E+14	4.50E+14	6.00E+14	7.50E+14	9.00E+14	1.05E+15
NH	1.03E-05	1.39E-05	1.73E-05	2.04E-05	2.34E-05	2.62E-05
NAOH	7.05E+13	8.71E+13	9.78E+13	1.02E+14	1.05E+14	1.09E+14
HOCL	5.40E+10	8.17E+10	1.14E+11	1.55E+11	2.00E+11	2.46E+11
CLO2	2.15E+03	3.61E+03	5.40E+03	7.80E+03	1.05E+04	1.34E+04
H2O	7.43E+20	1.12E+21	1.49E+21	1.86E+21	2.23E+21	2.60E+21
HO2	4.76E+10	7.90E+10	1.13E+11	1.50E+11	1.88E+11	2.26E+11
O3	7.23E+06	1.33E+07	2.05E+07	2.86E+07	3.76E+07	4.73E+07
NO2-	1.16E+02	1.56E+02	1.84E+02	1.99E+02	2.12E+02	2.24E+02
NO2	3.34E+13	6.14E+13	9.45E+13	1.32E+14	1.74E+14	2.19E+14
N2O	3.25E+10	5.97E+10	9.19E+10	1.28E+11	1.69E+11	2.13E+11
HNO	4.32E+06	7.17E+06	1.03E+07	1.36E+07	1.71E+07	2.07E+07
NO3-	8.23E+02	1.36E+03	1.84E+03	2.23E+03	2.61E+03	2.97E+03
NO3	1.23E+07	2.77E+07	4.92E+07	7.69E+07	1.11E+08	1.51E+08
N2O3	6.12E+03	1.69E+04	3.46E+04	6.05E+04	9.54E+04	1.40E+05
N2O4	2.15E+02	7.24E+02	1.72E+03	3.35E+03	5.79E+03	9.20E+03
N2O5	1.16E-01	4.81E-01	1.32E+00	2.87E+00	5.44E+00	9.33E+00
HNO2 (C)	1.94E+12	3.94E+12	6.52E+12	9.63E+12	1.33E+13	1.74E+13
HNO2 (T)	2.57E+12	5.23E+12	8.65E+12	1.28E+13	1.76E+13	2.30E+13
HNO3	5.60E+10	1.39E+11	2.66E+11	4.40E+11	6.63E+11	9.38E+11
NH3	7.96E+12	1.32E+13	1.89E+13	2.50E+13	3.14E+13	3.81E+13
NACL (C)	3.59E+17	4.62E+17	3.99E+17	1.20E+17	-2.94E+17	-7.12E+17
NAOH (C)	0.	0.	7.26E+12	2.69E+13	4.52E+13	6.24E+13
TOTAL	7.59E+20	1.14E+21	1.52E+21	1.90E+21	2.28E+21	2.66E+21

PRESSURE (BARS) OF 0.98 WATER + 0.02 AIR + NACL

TEMP. (DEG K)	LOG10 OF DENSITY RATIO (STANDARD DENSITY = 1.1500E-01 GM/CM3)									
	-.70	-.52	-.40	-.30	-.22	-.15	-.10	-.05	-.00	.04
600	5.560E+01	7.797E+01								
650	6.242E+01	8.940E+01	1.136E+02	1.349E+02						
700	6.830E+01	9.889E+01	1.269E+02	1.525E+02	1.757E+02	1.963E+02	2.145E+02			
750	7.462E+01	1.089E+02	1.410E+02	1.710E+02	1.986E+02	2.240E+02	2.469E+02	2.673E+02	2.852E+02	
775	7.739E+01	1.131E+02	1.468E+02	1.784E+02	2.078E+02	2.349E+02	2.596E+02	2.819E+02	3.018E+02	3.191E+02
800	7.949E+01	1.162E+02	1.509E+02	1.838E+02	2.150E+02	2.445E+02	2.724E+02	2.989E+02	3.240E+02	3.476E+02
850	8.504E+01	1.247E+02	1.627E+02	1.991E+02	2.340E+02	2.675E+02	2.997E+02	3.308E+02	3.609E+02	3.900E+02
900	9.059E+01	1.333E+02	1.745E+02	2.143E+02	2.528E+02	2.900E+02	3.262E+02	3.615E+02		
950	9.641E+01	1.425E+02	1.872E+02	2.308E+02	2.732E+02	3.146E+02				

Entries omitted where liquid phase exists.

ENERGY (ERG/GM) OF 0.98 WATER + 0.02 AIR + NACL

LOG10 OF DENSITY RATIO (STANDARD DENSITY = 1.1500E-01 GM/CM3)

TEMP. (DEG K)	-.70	-.52	-.40	-.30	-.22	-.15	-.10	-.05	-.00	.04
600	7.507E+09	7.058E+09								
650	8.404E+09	8.014E+09	7.633E+09	7.246E+09						
700	9.280E+09	8.941E+09	8.599E+09	8.258E+09	7.919E+09	7.582E+09	7.244E+09			
750	1.015E+10	9.845E+09	9.537E+09	9.230E+09	8.926E+09	8.624E+09	8.322E+09	8.018E+09	7.711E+09	
775	1.058E+10	1.029E+10	9.997E+09	9.703E+09	9.412E+09	9.124E+09	8.835E+09	8.545E+09	8.251E+09	7.938E+09
800	1.102E+10	1.074E+10	1.046E+10	1.018E+10	9.903E+09	9.628E+09	9.353E+09	9.077E+09	8.796E+09	8.496E+09
850	1.190E+10	1.164E+10	1.138E+10	1.112E+10	1.086E+10	1.061E+10	1.036E+10	1.010E+10	9.841E+09	9.562E+09
900	1.278E+10	1.254E+10	1.230E+10	1.206E+10	1.182E+10	1.158E+10	1.134E+10	1.110E+10		
950	1.368E+10	1.344E+10	1.320E+10	1.295E+10	1.270E+10	1.246E+10				

Entries omitted where liquid phase exists.

EQUILIBRIUM COMPOSITION FOR 0.99 WATER + 0.01 AIR + 7.2E-5 NACL (2000°K)

CONCENTRATIONS IN PARTICLES/CM3

LOG10 OF DENSITY RATIO (STANDARD DENSITY = 1.0000E+00 GM/CM3)

SPECIES	-4.50	-4.00	-3.50	-3.00	-2.50	-2.00	-1.50	-1.00	-.50	0.00	.50
E-	1.50E+10	1.51E+10	1.35E+10	1.13E+10	8.92E+09	6.87E+09	5.18E+09	3.82E+09	2.61E+09	9.63E+08	1.58E+07
NA	1.96E+13	3.25E+13	4.93E+13	7.07E+13	9.78E+13	1.30E+14	1.64E+14	1.74E+14	1.13E+14	1.55E+13	1.58E+10
NA+	3.16E+10	5.21E+10	8.82E+10	1.52E+11	2.66E+11	4.60E+11	7.65E+11	1.11E+12	1.05E+12	3.91E+11	2.42E+10
CL-	1.53E+10	3.40E+10	6.85E+10	1.29E+11	2.35E+11	4.14E+11	6.88E+11	9.67E+11	7.92E+11	7.93E+10	3.21E+06
CL	1.75E+12	3.88E+12	8.70E+12	1.98E+13	4.54E+13	1.04E+14	2.28E+14	4.36E+14	5.21E+14	1.42E+14	3.49E+11
H-	3.87E+05	5.53E+05	6.97E+05	8.02E+05	8.65E+05	8.82E+05	8.32E+05	6.52E+05	2.89E+05	1.47E+04	2.45E-01
H	2.80E+14	3.98E+14	5.59E+14	7.74E+14	1.05E+15	1.39E+15	1.74E+15	1.85E+15	1.20E+15	1.65E+14	1.68E+11
O-	1.13E+07	1.78E+07	2.56E+07	3.49E+07	4.64E+07	6.02E+07	7.43E+07	7.78E+07	4.71E+07	3.37E+06	8.72E+01
O	9.28E+13	1.45E+14	2.33E+14	3.82E+14	6.40E+14	1.08E+15	1.76E+15	2.51E+15	2.22E+15	4.31E+14	6.79E+11
N	1.55E+08	2.76E+08	4.90E+08	8.69E+08	1.53E+09	2.67E+09	4.47E+09	6.28E+09	5.52E+09	1.07E+09	1.70E+06
NACL	5.23E+12	1.92E+13	6.53E+13	2.10E+14	6.89E+14	2.20E+15	6.97E+15	2.21E+16	6.99E+16	2.20E+17	6.90E+17
NAO	1.26E+11	3.26E+11	7.94E+11	1.88E+12	4.41E+12	1.04E+13	2.45E+13	5.77E+13	1.35E+14	3.04E+14	6.10E+14
HCL	6.86E+13	2.16E+14	6.82E+14	2.16E+15	6.83E+15	2.16E+16	6.84E+16	2.16E+17	6.84E+17	2.16E+18	6.76E+18
NAH	7.99E+09	1.67E+10	3.57E+10	7.13E+10	1.36E+11	2.51E+11	4.52E+11	7.99E+11	1.37E+12	2.19E+12	2.82E+12
CL2	1.57E+06	7.71E+06	3.89E+07	2.02E+08	1.08E+09	5.89E+09	3.28E+10	1.86E+11	1.08E+12	6.76E+12	5.14E+13
NA2	7.17E+05	1.97E+06	4.54E+06	9.40E+06	1.82E+07	3.39E+07	6.13E+07	1.08E+08	1.86E+08	2.97E+08	3.83E+08
O2-	4.45E+06	1.10E+07	2.54E+07	5.70E+07	1.28E+08	2.94E+08	6.82E+08	1.58E+09	3.45E+09	4.06E+09	2.07E+08
O2	5.31E+15	1.31E+16	3.35E+16	9.07E+16	2.58E+17	7.67E+17	2.36E+18	7.43E+18	2.37E+19	7.55E+19	2.34E+20
O2+	6.00E-05	1.47E-04	4.20E-04	1.37E-03	4.90E-03	1.89E-02	7.72E-02	3.30E-01	1.54E+00	1.33E+01	2.51E+03
H2	8.12E+15	1.64E+16	3.25E+16	6.26E+16	1.17E+17	2.15E+17	3.87E+17	6.83E+17	1.17E+18	1.87E+18	2.41E+18
OH-	1.33E+09	2.99E+09	6.04E+09	1.15E+10	2.10E+10	3.77E+10	6.69E+10	1.16E+11	1.86E+11	1.55E+11	5.08E+09
OH	3.77E+15	8.41E+15	1.90E+16	4.31E+16	9.99E+16	2.33E+17	5.48E+17	1.29E+18	3.02E+18	6.81E+18	1.36E+19
OH+	0.	0.	0.	0.	0.	0.	1.03E-05	3.31E-05	1.13E-04	6.91E-04	8.44E-02
N2	8.21E+15	2.60E+16	8.21E+16	2.59E+17	8.19E+17	2.59E+18	8.16E+18	2.57E+19	8.10E+19	2.56E+20	8.11E+20
N2+	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	2.59E-05
NO	1.32E+14	3.67E+14	1.05E+15	3.06E+15	9.16E+15	2.81E+16	8.74E+16	2.75E+17	8.72E+17	2.77E+18	8.68E+18
NO+	3.39E+00	9.39E+00	2.98E+01	1.05E+02	3.97E+02	1.58E+03	6.51E+03	2.78E+04	1.29E+05	1.11E+06	2.12E+08
NH	1.27E+07	3.22E+07	8.04E+07	1.98E+08	4.83E+08	1.16E+09	2.76E+09	6.52E+09	1.51E+10	3.40E+10	6.88E+10
NAOH	5.07E+13	1.87E+14	6.41E+14	2.10E+15	6.77E+15	2.16E+16	6.85E+16	2.17E+17	6.86E+17	2.17E+18	6.86E+18
HOCL	3.08E+09	1.52E+10	7.68E+10	4.00E+11	2.13E+12	1.17E+13	6.49E+13	3.68E+14	2.15E+15	1.34E+16	1.03E+17
CLO2	4.93E+03	2.68E+04	1.55E+05	9.52E+05	6.26E+06	4.36E+07	3.17E+08	2.40E+09	1.91E+10	1.69E+11	2.01E+12
H2O	1.03E+18	3.27E+18	1.04E+19	3.28E+19	1.04E+20	3.28E+20	1.04E+21	3.29E+21	1.04E+22	3.29E+22	1.04E+23
HO2	2.17E+11	7.57E+11	2.73E+12	1.03E+13	4.00E+13	1.61E+14	6.67E+14	2.82E+15	1.22E+16	5.43E+16	2.66E+17
O3	1.01E+07	3.89E+07	1.60E+08	7.12E+08	3.42E+09	1.75E+10	9.50E+10	5.36E+11	3.15E+12	1.99E+13	1.51E+14
NO2-	8.09E+05	3.55E+06	1.46E+07	5.82E+07	2.33E+08	9.50E+08	3.93E+09	1.63E+10	6.54E+10	1.52E+11	1.91E+10
NO2	1.84E+10	8.05E+10	3.68E+11	1.77E+12	8.94E+12	4.73E+13	2.59E+14	1.46E+15	8.56E+15	5.38E+16	4.13E+17
N2O	3.66E+08	1.81E+09	9.19E+09	4.77E+10	2.54E+11	1.39E+12	7.69E+12	4.35E+13	2.53E+14	1.58E+15	1.23E+16
HNO	2.52E+09	1.00E+10	4.01E+10	1.63E+11	6.67E+11	2.77E+12	1.16E+13	4.91E+13	2.11E+14	9.36E+14	4.64E+15
NA2CL2	3.46E+05	4.92E+06	5.72E+07	6.15E+08	6.36E+09	6.46E+10	6.51E+11	6.53E+12	6.54E+13	6.50E+14	6.38E+15
HNO2 (T)	7.71E+08	4.79E+09	3.08E+10	2.05E+11	1.42E+12	1.02E+13	7.45E+13	5.53E+14	4.10E+15	2.93E+16	1.84E+17
HNO3	2.76E+04	2.69E+05	2.77E+06	3.04E+07	3.55E+08	4.38E+09	5.64E+10	7.51E+11	1.03E+13	1.46E+14	2.24E+15
NH3	1.62E+13	8.32E+13	4.11E+14	1.95E+15	8.92E+15	3.93E+16	1.68E+17	7.90E+17	2.79E+18	9.98E+18	2.61E+19
TOTAL	1.06E+18	3.33E+18	1.05E+19	3.33E+19	1.05E+20	3.32E+20	1.05E+21	3.32E+21	1.05E+22	3.32E+22	1.05E+23

EQUILIBRIUM COMPOSITION FOR 0.99 WATER + 0.01 AIR + 7.2E-5 NACL (3000°K)

CONCENTRATIONS IN PARTICLES/CM3

SPECIES	LOG10 OF DENSITY RATIO (STANDARD DENSITY = 1.0000E+00 GM/CM3)										
	-4.50	-4.00	-3.50	-3.00	-2.50	-2.00	-1.50	-1.00	-.50	0.00	.50
E-	7.05E+12	1.13E+13	1.62E+13	2.03E+13	2.20E+13	2.11E+13	1.83E+13	1.42E+13	8.97E+12	3.14E+12	2.09E+11
NA	5.74E+13	1.59E+14	3.81E+14	7.72E+14	1.36E+15	2.15E+15	3.08E+15	3.76E+15	3.02E+15	6.93E+14	3.17E+12
NA+	7.55E+12	1.31E+13	2.18E+13	3.54E+13	5.76E+13	9.50E+13	1.57E+14	2.46E+14	3.13E+14	2.04E+14	1.40E+13
CL-	4.01E+10	1.46E+11	4.69E+11	1.30E+12	3.09E+12	6.42E+12	1.17E+13	1.75E+13	1.54E+13	2.66E+12	2.95E+09
CL	2.04E+13	4.64E+13	1.04E+14	2.39E+14	5.05E+14	1.09E+15	2.31E+15	4.42E+15	6.18E+15	3.04E+15	5.08E+13
CL+	4.58E-01	6.50E-01	1.01E+00	1.80E+00	3.64E+00	8.25E+00	2.00E+01	4.93E+01	1.09E+02	1.53E+02	3.83E+01
H-	9.39E+09	2.24E+10	4.85E+10	9.02E+10	1.44E+11	1.99E+11	2.36E+11	2.20E+11	1.11E+11	8.89E+09	2.71E+06
H	1.11E+17	1.70E+17	2.56E+17	3.81E+17	5.61E+17	8.08E+17	1.11E+18	1.33E+18	1.06E+18	2.43E+17	1.11E+15
H+	8.44E+01	8.57E+01	9.02E+01	1.04E+02	1.46E+02	2.20E+02	3.48E+02	5.35E+02	6.73E+02	4.39E+02	3.03E+01
O-	8.37E+10	2.05E+11	4.44E+11	8.32E+11	1.34E+12	1.90E+12	2.37E+12	2.40E+12	1.40E+12	1.43E+11	5.66E+07
O	4.68E+16	7.14E+16	1.08E+17	1.61E+17	2.40E+17	3.55E+17	5.10E+17	6.65E+17	6.15E+17	1.79E+17	1.25E+15
O+	3.24E+01	3.08E+01	3.25E+01	3.89E+01	5.35E+01	8.25E+01	1.37E+02	2.29E+02	3.34E+02	2.77E+02	2.92E+01
N	1.80E+12	3.23E+12	5.80E+12	1.04E+13	1.84E+13	3.22E+13	5.39E+13	7.99E+13	8.26E+13	2.78E+13	2.60E+11
N+	1.69E-04	1.90E-04	2.38E-04	3.40E-04	5.58E-04	1.02E-03	1.96E-03	3.74E-03	6.11E-03	5.86E-03	8.23E-04
NACL	5.92E+10	3.73E+11	2.00E+12	9.01E+12	3.52E+13	1.25E+14	4.18E+14	1.36E+15	4.37E+15	1.38E+16	4.19E+16
NAO	1.01E+12	4.30E+12	1.55E+13	4.72E+13	1.25E+14	3.02E+14	6.91E+14	1.53E+15	3.25E+15	6.09E+15	7.74E+15
HCL	5.51E+13	1.92E+14	6.50E+14	2.15E+15	7.01E+15	2.27E+16	7.27E+16	2.32E+17	7.41E+17	2.34E+18	7.13E+18
NAH	1.80E+11	7.68E+11	2.77E+12	8.40E+12	2.20E+13	5.17E+13	1.13E+14	2.30E+14	4.22E+14	6.21E+14	5.18E+14
CL2	1.92E+06	9.91E+06	4.97E+07	2.45E+08	1.19E+09	5.79E+09	2.85E+10	1.46E+11	8.15E+11	5.53E+12	6.13E+13
NA2	1.98E+06	1.14E+07	6.51E+07	2.69E+08	8.43E+08	2.18E+09	4.97E+09	1.03E+10	1.90E+10	2.80E+10	2.33E+10
O2-	6.77E+09	2.53E+10	8.28E+10	2.33E+11	5.66E+11	1.22E+12	2.43E+12	4.48E+12	6.91E+12	5.77E+12	7.45E+11
O2	7.08E+16	1.65E+17	3.76E+17	8.46E+17	1.90E+18	4.28E+18	9.81E+18	2.32E+19	5.68E+19	1.35E+20	2.63E+20
O2+	4.20E+04	6.12E+04	9.71E+04	1.75E+05	3.62E+05	8.52E+05	2.26E+06	6.86E+06	2.65E+07	1.80E+08	5.24E+09
H2	2.02E+17	4.76E+17	1.08E+18	2.41E+18	5.28E+18	1.13E+19	2.37E+19	4.73E+19	8.60E+19	1.27E+20	1.06E+20
OH-	3.98E+11	1.38E+12	4.53E+12	1.27E+13	3.04E+13	6.40E+13	1.22E+14	2.06E+14	2.74E+14	1.80E+14	1.52E+13
OH	1.42E+17	3.32E+17	7.57E+17	1.69E+18	3.75E+18	8.25E+18	1.81E+19	3.93E+19	8.29E+19	1.55E+20	1.98E+20
OH+	5.98E+02	8.76E+02	1.39E+03	2.49E+03	5.09E+03	1.17E+04	2.96E+04	8.25E+04	2.75E+05	1.47E+06	2.81E+07
N2	6.92E+15	2.24E+16	7.23E+16	2.32E+17	7.39E+17	2.33E+18	7.25E+18	2.22E+19	6.80E+19	2.16E+20	7.49E+20
N2+	1.17E-02	2.36E-02	5.31E-02	1.36E-01	4.01E-01	1.32E+00	4.74E+00	1.87E+01	9.02E+01	8.16E+02	4.25E+04
NO	2.70E+15	7.41E+15	2.01E+16	5.40E+16	1.44E+17	3.85E+17	1.03E+18	2.77E+18	7.57E+18	2.08E+19	5.41E+19
NO+	1.58E+07	2.71E+07	5.12E+07	1.10E+08	2.71E+08	7.56E+08	2.33E+09	8.06E+09	3.48E+10	2.73E+11	1.06E+13
NH	1.13E+11	3.11E+11	8.44E+11	2.24E+12	5.95E+12	1.55E+13	3.95E+13	9.78E+13	2.31E+14	4.99E+14	8.50E+14
NAOH	9.42E+12	6.13E+13	3.34E+14	1.52E+15	5.96E+15	2.12E+16	7.12E+16	2.32E+17	7.45E+17	2.37E+18	7.51E+18
HOCL	1.09E+10	5.79E+10	2.96E+11	1.47E+12	7.18E+12	3.50E+13	1.73E+14	8.84E+14	4.94E+15	3.37E+16	3.90E+17
CLO2	7.57E+05	3.91E+06	1.99E+07	9.96E+07	4.93E+08	2.47E+09	1.27E+10	7.10E+10	4.60E+11	3.99E+12	7.05E+13
H2O	7.12E+17	2.56E+18	8.81E+18	2.94E+19	9.65E+19	3.13E+20	1.01E+21	3.21E+21	1.02E+22	3.26E+22	1.04E+23
HO2	2.41E+13	8.63E+13	2.97E+14	9.96E+14	3.31E+15	1.10E+16	3.70E+16	1.29E+17	4.76E+17	1.92E+18	9.33E+18
O3	1.09E+10	3.90E+10	1.34E+11	4.52E+11	1.52E+12	5.18E+12	1.83E+13	6.92E+13	2.96E+14	1.52E+15	1.13E+16
NO2-	5.14E+07	3.46E+08	2.03E+09	1.03E+10	4.46E+10	1.72E+11	6.11E+11	2.05E+12	6.21E+12	1.29E+13	8.48E+12
NO2	5.40E+11	2.27E+12	9.27E+12	3.74E+13	1.50E+14	6.03E+14	2.48E+15	1.07E+16	5.12E+16	3.04E+17	3.00E+18
N2O	8.39E+09	4.15E+10	2.02E+11	9.73E+11	4.65E+12	2.21E+13	1.06E+14	5.20E+14	2.79E+15	1.51E+16	2.52E+17
HNO	3.60E+11	1.52E+12	6.22E+12	2.49E+13	9.87E+13	3.88E+14	1.52E+15	6.02E+15	2.49E+16	1.16E+17	7.53E+17
NA2CL2	1.55E+00	6.17E+01	1.77E+03	3.59E+04	5.48E+05	6.88E+06	7.73E+07	8.22E+08	8.47E+09	8.46E+10	7.79E+11
HNO2 (T)	1.61E+10	1.04E+11	6.40E+11	3.85E+12	2.26E+13	1.33E+14	7.82E+14	4.58E+15	2.64E+16	1.36E+17	4.50E+17
HNO3	9.71E+05	9.56E+06	8.91E+07	8.03E+08	7.13E+09	6.32E+10	5.68E+11	5.33E+12	5.38E+13	5.99E+14	7.54E+15
NH3	2.53E+13	1.65E+14	1.02E+15	6.05E+15	3.49E+16	1.95E+17	1.04E+18	5.14E+18	2.20E+19	7.03E+19	1.00E+20
TOTAL	1.29E+18	3.81E+18	1.15E+19	3.52E+19	1.09E+20	3.41E+20	1.07E+21	3.36E+21	1.06E+22	3.33E+22	1.05E+23

EQUILIBRIUM COMPOSITION FOR 0.99 WATER + 0.01 AIR + 7.2E-5 NACL (4000°K)

CONCENTRATIONS IN PARTICLES/CM3

SPECIES	LOG10 OF DENSITY RATIO (STANDARD DENSITY = 1.0000E+00 GM/CM3)									
	-4.50	-4.00	-3.50	-3.00	-2.50	-2.00	-1.50	-1.00	-.50	0.00
E-	5.09E+13	1.30E+14	2.50E+14	4.00E+14	5.29E+14	5.85E+14	5.59E+14	4.72E+14	3.33E+14	1.48E+14
NA	1.63E+13	8.91E+13	3.66E+14	1.15E+15	2.82E+15	5.56E+15	9.16E+15	1.24E+16	1.15E+16	3.60E+15
NA+	5.88E+13	1.42E+14	3.04E+14	6.09E+14	1.12E+15	1.99E+15	3.44E+15	5.51E+15	7.18E+15	5.02E+15
CL-	1.67E+10	9.52E+10	4.37E+11	1.62E+12	4.83E+12	1.18E+13	2.42E+13	4.06E+13	4.41E+13	1.29E+13
CL	5.49E+13	1.37E+14	3.27E+14	7.55E+14	1.71E+15	3.77E+15	8.10E+15	1.61E+16	2.48E+16	1.63E+16
CL+	7.03E+04	7.73E+04	9.64E+04	1.40E+05	2.39E+05	4.80E+05	1.08E+06	2.53E+06	5.49E+06	8.03E+06
H-	2.34E+11	1.05E+12	3.56E+12	9.40E+12	1.96E+13	3.27E+13	4.49E+13	4.83E+13	3.07E+13	4.29E+12
H	1.13E+18	2.21E+18	3.91E+18	6.43E+18	1.01E+19	1.53E+19	2.20E+19	2.80E+19	2.53E+19	7.93E+18
H+	9.00E+07	7.78E+07	7.18E+07	7.41E+07	8.84E+07	1.21E+08	1.83E+08	2.75E+08	3.49E+08	2.44E+08
O-	1.27E+12	5.71E+12	1.94E+13	5.12E+13	1.07E+14	1.79E+14	2.48E+14	2.72E+14	1.81E+14	2.76E+13
O	5.66E+17	1.11E+18	1.97E+18	3.20E+18	5.11E+18	7.76E+18	1.12E+19	1.46E+19	1.38E+19	4.71E+18
O+	3.10E+07	3.38E+07	3.12E+07	3.22E+07	3.85E+07	5.31E+07	8.04E+07	1.23E+08	1.64E+08	1.25E+08
N	1.71E+14	2.98E+14	5.30E+14	9.57E+14	1.73E+15	3.08E+15	5.28E+15	8.15E+15	9.30E+15	4.27E+15
N+	3.97E+03	3.04E+03	2.83E+03	3.20E+03	4.38E+03	7.09E+03	1.27E+04	2.32E+04	3.73E+04	3.81E+04
NACL	8.65E+08	1.18E+10	1.16E+11	8.44E+11	4.70E+12	2.10E+13	8.07E+13	2.83E+14	9.46E+14	3.02E+15
NAO	2.71E+11	2.92E+12	2.12E+13	1.10E+14	4.27E+14	1.31E+15	3.40E+15	7.81E+15	1.59E+16	2.66E+16
HCL	2.37E+13	1.02E+14	4.28E+14	1.63E+15	5.04E+15	2.00E+16	6.71E+16	2.21E+17	7.20E+17	2.30E+18
NAH	8.16E+10	8.79E+11	6.37E+12	3.30E+13	1.28E+14	3.92E+14	1.01E+15	2.27E+15	4.43E+15	6.77E+15
CL2	1.39E+06	8.70E+06	4.94E+07	2.64E+08	1.36E+09	6.81E+09	3.40E+10	1.75E+11	9.73E+11	6.50E+12
NA2	5.27E+04	1.58E+06	2.67E+07	2.63E+08	1.60E+09	6.37E+09	1.88E+10	4.50E+10	9.01E+10	1.38E+11
O2-	2.63E+10	2.33E+11	1.40E+12	6.09E+12	2.01E+13	5.26E+13	1.15E+14	2.13E+14	3.12E+14	2.53E+14
O2	7.79E+16	3.10E+17	9.67E+17	2.63E+18	6.57E+18	1.55E+19	3.54E+19	7.79E+19	1.62E+20	2.95E+20
O2+	1.03E+09	1.75E+09	2.66E+09	4.89E+09	9.26E+09	1.99E+10	4.74E+10	1.23E+11	3.62E+11	1.47E+12
H2	2.75E+17	1.06E+18	3.31E+18	8.98E+18	2.24E+19	5.26E+19	1.18E+20	2.49E+20	4.75E+20	7.25E+20
OH-	5.71E+11	5.05E+12	3.03E+13	1.32E+14	4.35E+14	1.13E+15	2.45E+15	4.46E+15	6.26E+15	4.65E+15
OH	2.22E+17	8.58E+17	2.67E+18	7.27E+18	1.81E+19	4.27E+19	9.66E+19	2.08E+20	4.15E+20	6.92E+20
OH+	8.29E+07	1.41E+08	2.30E+08	3.92E+08	7.42E+08	1.59E+09	3.75E+09	9.55E+09	2.69E+10	9.98E+10
N2	5.16E+15	1.56E+16	4.95E+16	1.61E+17	5.31E+17	1.73E+18	5.51E+18	1.71E+19	5.23E+19	1.71E+20
N2+	6.26E+03	8.34E+03	1.38E+04	2.83E+04	7.05E+04	2.08E+05	6.95E+05	2.54E+06	1.10E+07	7.99E+07
NO	6.07E+15	2.08E+16	6.54E+16	1.95E+17	5.58E+17	1.55E+19	4.17E+18	1.09E+19	2.75E+19	6.70E+19
NO+	5.15E+10	7.76E+10	1.28E+11	2.30E+11	5.18E+11	1.31E+12	3.68E+12	1.13E+13	4.04E+13	2.20E+14
NH	5.06E+12	1.73E+13	5.43E+13	1.62E+14	4.63E+14	1.28E+15	3.42E+15	8.76E+15	2.12E+16	4.72E+16
NAOH	2.14E+11	4.54E+12	5.82E+13	4.98E+14	3.07E+15	1.46E+16	5.85E+16	2.11E+17	7.16E+17	2.35E+18
HOCL	4.91E+09	4.75E+10	3.53E+11	2.22E+12	1.26E+13	6.76E+13	3.52E+14	1.85E+15	1.05E+16	7.21E+16
CLO2	2.32E+06	2.25E+07	1.67E+08	1.06E+09	6.00E+09	3.22E+10	1.69E+11	9.09E+11	5.38E+12	4.03E+13
H2O	9.07E+16	6.90E+17	3.80E+18	1.70E+19	6.74E+19	2.47E+20	8.61E+20	2.91E+21	9.65E+21	3.16E+22
HO2	4.18E+13	3.19E+14	1.76E+15	7.89E+15	3.13E+16	1.15E+17	4.04E+17	1.39E+18	4.82E+18	1.73E+19
O3	6.33E+10	4.83E+11	2.66E+12	1.20E+13	4.75E+13	1.75E+14	6.21E+14	2.18E+15	7.91E+15	3.09E+16
NO2-	3.87E+07	5.97E+08	6.39E+09	5.04E+10	3.04E+11	1.45E+12	5.81E+12	2.05E+13	6.34E+13	1.48E+14
NO2	8.42E+11	5.68E+12	3.16E+13	1.56E+14	7.08E+14	3.06E+15	1.28E+16	5.36E+16	2.35E+17	1.23E+18
N2O	1.48E+10	1.18E+11	6.62E+11	3.57E+12	1.86E+13	9.45E+13	4.69E+14	2.32E+15	1.24E+16	8.66E+16
HNO	1.17E+12	7.87E+12	4.37E+13	2.15E+14	9.77E+14	4.21E+15	1.75E+16	7.17E+16	3.01E+17	1.44E+18
NA2CL2	6.48E-05	1.29E-02	1.24E+00	6.55E+01	2.03E+03	4.97E+04	6.00E+05	7.39E+06	8.23E+07	8.39E+08
HNO2 (T)	1.21E+10	1.60E+11	1.57E+12	1.27E+13	9.07E+13	5.94E+14	3.62E+15	2.04E+16	1.02E+17	4.16E+17
HNO3	2.75E+05	1.50E+07	2.60E+08	3.48E+09	3.95E+10	4.03E+11	3.82E+12	3.44E+13	3.01E+14	2.62E+15
NH3	4.36E+12	6.02E+13	5.89E+14	4.76E+15	3.39E+16	2.20E+17	1.32E+18	7.14E+18	3.29E+19	1.12E+20
TOTAL	2.37E+18	6.29E+18	1.67E+19	4.60E+19	1.31E+20	3.84E+20	1.16E+21	3.52E+21	1.09E+22	3.37E+22

EQUILIBRIUM COMPOSITION FOR 0.99 WATER + 0.01 AIR + 7.2E-5 NACL (6000°K)

CONCENTRATIONS IN PARTICLES/CM3

SPECIES	LOG10 OF DENSITY RATIO -4.50	-4.00	-3.50	-3.00	-2.50	-2.00	-1.50	-1.00	-.50	0.00
E-	1.93E+10	4.62E+14	1.12E+15	2.62E+15	5.52E+15	9.73E+15	1.38E+16	1.58E+16	1.52E+16	1.26E+16
NA	2.82E+11	2.17E+12	1.59E+13	1.17E+14	6.87E+14	3.27E+15	1.11E+16	2.55E+16	3.45E+16	1.66E+16
NA+	7.54E+13	2.37E+14	7.40E+14	2.27E+15	6.69E+15	1.84E+16	4.48E+16	9.01E+16	1.27E+17	7.29E+16
CL-	1.24E+09	9.21E+09	6.70E+10	4.39E+11	2.40E+12	1.02E+13	3.29E+13	8.13E+13	1.42E+14	1.10E+14
CL	7.49E+13	2.32E+14	6.95E+14	1.95E+15	5.06E+15	1.22E+16	2.78E+16	5.98E+16	1.08E+17	1.02E+17
CL+	1.57E+10	2.05E+10	2.55E+10	3.10E+10	3.88E+10	5.40E+10	8.83E+10	1.66E+11	3.13E+11	3.53E+11
H+	3.77E+11	2.75E+12	1.92E+13	1.14E+14	5.28E+14	1.79E+15	4.35E+15	7.36E+15	7.54E+15	2.77E+15
H	2.04E+18	6.22E+18	1.78E+19	4.53E+19	9.98E+19	1.92E+20	3.29E+20	4.85E+20	5.18E+20	2.30E+20
H-	4.50E+13	5.80E+13	6.89E+13	7.62E+13	8.10E+13	9.00E+13	1.10E+14	1.43E+14	1.58E+14	8.43E+13
O-	[illegible].01E+12	7.38E+12	5.18E+13	3.13E+14	1.48E+15	5.14E+15	1.26E+16	2.16E+16	2.23E+16	8.14E+15
O	1.63E+18	3.13E+18	9.05E+18	2.34E+19	5.27E+19	1.03E+20	1.80E+20	2.68E+20	2.87E+20	1.27E+20
O+	1.97E+13	2.53E+13	3.03E+13	3.41E+13	3.70E+13	4.19E+13	5.22E+13	6.80E+13	7.60E+13	4.02E+13
N	1.33E+16	2.45E+16	4.66E+16	8.14E+16	1.39E+17	2.39E+17	4.13E+17	6.82E+17	9.17E+17	6.19E+17
N+	1.79E+11	1.64E+11	1.29E+11	9.78E+10	8.04E+10	8.00E+10	9.93E+10	1.43E+11	2.01E+11	1.62E+11
NACL	3.92E+05	9.11E+06	2.05E+08	4.07E+09	6.44E+10	7.44E+11	6.00E+12	3.47E+13	1.56E+14	5.67E+14
NAO	6.40E+09	1.47E+10	3.18E+11	5.81E+12	7.99E+13	7.52E+14	4.62E+15	1.85E+16	4.92E+16	8.42E+16
HCL	7.57E+11	7.14E+12	6.12E+13	4.39E+14	2.50E+15	1.17E+16	4.73E+16	1.76E+17	6.25E+17	2.10E+18
NAH	3.95E+08	9.02E+09	1.94E+11	3.49E+12	4.69E+13	4.32E+14	2.62E+15	1.04E+16	2.75E+16	4.73E+16
CL2	2.75E+05	2.64E+06	2.37E+07	1.87E+08	1.25E+09	7.34E+09	3.97E+10	2.15E+11	1.30E+12	9.21E+12
NA2	5.23E+00	2.94E+02	1.66E+04	8.28E+05	3.09E+07	7.06E+08	8.50E+09	5.25E+10	1.76E+11	3.27E+11
O2-	8.45E+08	1.89E+10	3.82E+11	5.49E+12	6.38E+13	4.37E+14	1.94E+15	5.80E+15	1.17E+16	1.53E+16
O2	2.25E+15	2.10E+16	1.75E+17	1.17E+18	5.93E+18	2.30E+19	7.21E+19	1.88E+20	3.96E+20	6.24E+20
O2+	1.59E+12	6.61E+12	2.29E+13	6.66E+13	1.63E+14	3.64E+14	8.19E+14	1.86E+15	4.09E+15	7.73E+15
H2	1.29E+16	1.20E+17	9.80E+17	6.36E+18	3.08E+19	1.15E+20	3.50E+20	8.94E+20	1.87E+21	2.97E+21
OH-	8.35E+09	1.97E+11	3.96E+12	6.19E+13	6.35E+14	4.26E+15	1.87E+16	5.53E+16	1.11E+17	1.46E+17
OH	1.24E+16	1.15E+17	9.53E+17	6.20E+18	3.11E+19	1.18E+20	3.66E+20	9.43E+20	1.98E+21	3.14E+21
OH+	9.35E+11	3.65E+12	1.25E+13	3.58E+13	8.56E+13	1.88E+14	4.17E+14	9.40E+14	2.05E+15	3.90E+15
N2	1.87E+15	8.87E+15	3.20E+16	9.73E+16	2.82E+17	8.43E+17	2.63E+18	8.39E+18	2.78E+19	1.02E+20
N2+	5.15E+09	1.02E+10	1.53E+10	2.02E+10	2.82E+10	4.87E+10	1.09E+11	3.04E+11	1.05E+12	4.62E+12
NO	[illegible].47E+15	9.77E+15	5.36E+16	2.42E+17	9.26E+17	3.15E+18	9.86E+18	2.84E+19	7.51E+19	1.81E+20
NO+	[illegible].77E+13	1.41E+14	3.22E+14	6.31E+14	1.17E+15	2.29E+15	5.14E+15	1.30E+16	3.57E+16	1.03E+17
NH	[illegible]	[illegible].99E+14	1.08E+15	4.81E+15	1.60E+16	4.02E+16	1.86E+17	5.30E+17	1.39E+18	3.37E+18
NAOH	9.34E+06	5.51E+08	4.05E+10	1.89E+12	5.76E+13	1.08E+15	1.24E+16	9.46E+16	5.18E+17	2.17E+18
HCO	3.47E+07	1.00E+09	2.48E+10	4.61E+11	5.96E+12	5.63E+13	4.35E+14	3.11E+15	2.29E+16	1.87E+17
CLO2	9.69E+04	2.80E+06	6.99E+07	1.32E+09	1.75E+10	1.68E+11	1.32E+12	9.51E+12	7.03E+13	5.72E+14
H2O	6.26E+13	1.78E+15	4.20E+16	7.07E+17	7.77E+18	5.86E+19	3.40E+20	1.67E+21	7.22E+21	2.80E+22
HO2	5.3[illegible]E+11	9.49E+12	2.26E+14	3.88E+15	4.35E+16	3.35E+17	1.97E+18	9.75E+18	4.25E+19	1.64E+20
O3	1.42E+09	4.08E+10	9.77E+11	1.79E+13	1.95E+14	1.53E+15	9.16E+15	4.57E+16	2.00E+17	7.66E+17
NO2-	1.82E+05	2.88E+06	3.42E+08	9.35E+09	1.71E+11	2.08E+12	1.75E+13	1.11E+14	5.86E+14	2.84E+15
NO2	2.32E+10	4.72E+11	7.47E+12	8.74E+13	7.61E+14	5.25E+15	3.12E+16	1.73E+17	9.47E+17	5.55E+18
N2O	3.98E+09	5.76E+10	6.01E+11	4.74E+12	3.12E+13	1.89E+14	1.12E+15	6.86E+15	4.71E+16	4.22E+17
HNO	7.97E+10	1.61E+12	2.54E+13	2.92E+14	2.48E+15	1.68E+16	9.85E+16	5.40E+17	2.94E+18	1.73E+19
NA2CL2	0.	0.	0.	4.08E-04	1.02E-01	1.37E+01	8.90E+02	2.98E+04	6.81E+05	7.94E+06
HNO2 (T)	5.55E+07	2.07E+09	9.37E+10	2.79E+12	5.28E+13	6.85E+14	6.62E+15	4.92E+16	2.73E+17	1.04E+18
HNO3	7.22E+02	4.20E+04	5.49E+06	4.25E+08	1.83E+10	4.79E+11	8.82E+12	1.26E+14	1.45E+15	1.34E+16
NH3	[illegible].23E+09	2.60E+11	1.16E+13	3.34E+14	6.05E+15	7.54E+16	7.89E+17	5.17E+18	2.84E+19	1.09E+20
TOTAL	3.[illegible]E+18	9.65E+18	2.91E+19	8.37E+19	2.29E+20	6.15E+20	1.65E+21	4.58E+21	1.24E+22	3.57E+22

(STANDARD DENSITY = 1.0000E+00 GM/CM3)

EQUILIBRIUM COMPOSITION FOR 0.99 WATER + 0.01 AIR + 7.2E-5 NACL (8000°K)

CONCENTRATIONS IN PARTICLES/CM3

SPECIES	LOG10 OF DENSITY RATIO (STANDARD DENSITY = 1.0000E+00 GM/CM3)									
	-4.50	-4.00	-3.50	-3.00	-2.50	-2.00	-1.50	-1.00	-.50	0.00
E-	3.85E+15	6.96E+15	1.27E+16	2.37E+16	4.39E+16	7.58E+16	1.15E+17	1.55E+17	1.91E+17	2.34E+17
NA	8.05E+11	3.90E+12	1.93E+13	6.23E+13	3.67E+14	1.75E+15	7.50E+15	2.55E+16	5.53E+16	3.92E+16
NA+	7.48E+13	2.35E+14	7.37E+14	2.33E+15	7.18E+15	2.17E+16	6.24E+16	1.63E+17	2.94E+17	1.74E+17
CL-	2.76E+09	1.58E+10	9.09E+10	5.22E+11	2.86E+12	1.37E+13	5.29E+13	1.66E+14	4.20E+14	6.08E+14
CL	7.48E+13	2.37E+14	7.44E+14	2.30E+15	6.81E+15	1.88E+16	4.79E+16	1.12E+17	2.30E+17	2.72E+17
CL+	6.95E+11	1.23E+12	2.14E+12	3.62E+12	5.95E+12	9.84E+12	1.69E+13	3.04E+13	5.14E+13	5.10E+13
CL++	3.24E+02	3.23E+02	3.16E+02	2.77E+02	2.53E+02	2.50E+02	2.92E+02	3.99E+02	5.60E+02	4.65E+02
H-	3.45E+12	1.96E+13	1.12E+14	6.29E+14	3.26E+15	1.40E+16	4.56E+16	1.11E+17	1.80E+17	1.26E+17
H	2.07E+18	6.52E+18	2.03E+19	6.13E+19	1.72E+20	4.26E+20	9.13E+20	1.65E+21	2.18E+21	1.25E+21
H+	2.60E+15	4.57E+15	7.88E+15	1.30E+16	2.03E+16	3.00E+16	4.36E+16	6.04E+16	6.57E+16	3.15E+16
O-	6.37E+12	3.63E+13	2.07E+14	1.17E+15	6.19E+15	2.73E+16	9.23E+16	2.31E+17	3.79E+17	2.56E+17
O	1.04E+18	3.28E+18	1.02E+19	3.11E+19	8.86E+19	2.26E+20	5.03E+20	9.38E+20	1.25E+21	6.90E+20
O+	1.13E+15	1.99E+15	3.44E+15	5.72E+15	9.06E+15	1.36E+16	2.08E+16	2.97E+16	3.27E+16	1.51E+16
N	1.63E+16	5.05E+16	1.50E+17	4.01E+17	9.18E+17	1.81E+18	3.27E+18	5.62E+18	8.30E+18	7.13E+18
N+	2.23E+13	3.85E+13	6.32E+13	9.28E+13	1.18E+14	1.39E+14	1.70E+14	2.23E+14	2.76E+14	1.96E+14
N++	3.06E+00	2.98E+00	2.75E+00	2.04E+00	1.46E+00	1.04E+00	8.62E-01	8.65E-01	2.85E-01	5.27E-01
NACL	5.80E+04	1.03E+06	1.83E+07	3.26E+08	5.35E+09	7.42E+10	8.07E+11	6.84E+12	4.54E+13	2.06E+14
NAO	1.82E+08	3.22E+09	5.68E+10	9.94E+11	1.57E+13	2.01E+14	1.91E+15	1.29E+16	5.57E+16	1.18E+17
HCL	9.48E+10	9.85E+11	9.63E+12	8.95E+13	7.41E+14	5.04E+15	2.74E+16	1.26E+17	4.99E+17	1.82E+18
NAH	1.63E+08	2.39E+09	5.09E+10	4.85E+11	1.37E+13	1.71E+14	1.57E+15	1.03E+16	4.38E+16	9.59E+16
CL2	4.93E+04	8.95E+05	8.83E+06	8.40E+07	7.35E+08	5.58E+09	3.60E+10	2.11E+11	1.32E+12	9.98E+12
NA2	2.90E+00	9.18E+01	2.93E+03	9.74E+04	3.00E+06	7.60E+07	1.39E+09	1.71E+10	1.21E+11	3.27E+11
O2-	8.26E+08	1.48E+10	2.64E+11	4.52E+12	6.78E+13	7.58E+14	5.68E+15	2.63E+16	9.24E+16	1.84E+17
O2	2.30E+14	2.26E+15	2.22E+16	2.04E+17	1.66E+18	1.07E+19	5.27E+19	1.96E+20	5.19E+20	8.54E+20
O2+	4.36E+12	2.42E+13	1.30E+14	6.56E+14	2.95E+15	1.14E+16	3.81E+16	1.08E+17	2.37E+17	3.27E+17
H2	1.73E+15	1.71E+16	1.66E+17	1.51E+18	1.18E+19	7.21E+19	3.30E+20	1.16E+21	2.99E+21	5.28E+21
OH-	6.25E+09	1.12E+11	1.99E+12	3.34E+13	5.00E+14	5.42E+15	3.92E+16	1.90E+17	6.12E+17	1.28E+18
OH	1.64E+15	1.63E+16	1.58E+17	1.44E+18	1.15E+19	7.24E+19	3.44E+20	1.24E+21	3.24E+21	5.53E+21
OH+	6.26E+12	3.48E+13	1.87E+14	9.37E+14	4.14E+15	1.56E+16	5.01E+16	1.38E+17	2.98E+17	4.26E+17
N2	3.45E+13	3.30E+14	2.89E+15	2.07E+16	1.08E+17	4.17E+17	1.36E+18	4.28E+18	1.42E+19	5.55E+19
N2+	1.65E+10	5.61E+10	4.27E+11	1.68E+12	4.86E+12	1.12E+13	2.48E+13	5.96E+13	1.64E+14	5.35E+14
NO	9.77E+13	9.50E+14	8.77E+15	7.12E+16	4.63E+17	2.31E+18	9.28E+18	3.17E+19	9.40E+19	2.38E+20
NO+	2.28E+13	1.24E+14	6.33E+14	2.82E+15	1.02E+16	3.04E+16	8.25E+16	2.16E+17	5.29E+17	1.12E+18
NH	1.01E+13	9.83E+13	9.05E+14	7.31E+15	4.68E+16	2.27E+17	8.78E+17	2.91E+18	8.53E+18	2.24E+19
NAOH	7.92E+05	3.81E+07	1.83E+09	5.81E+10	2.41E+12	7.81E+13	1.71E+15	2.70E+16	3.08E+17	1.96E+18
HOCL	1.58E+06	4.96E+07	1.51E+09	4.28E+10	1.02E+12	1.60E+13	2.35E+14	2.56E+15	2.74E+16	2.92E+17
CLO2	1.06E+04	3.33E+05	1.02E+07	2.90E+08	6.99E+09	1.28E+11	1.73E+12	1.93E+13	2.10E+14	2.16E+15
H2O	7.80E+11	2.43E+13	7.35E+14	2.03E+16	4.56E+17	7.26E+18	7.97E+19	6.72E+20	4.62E+21	2.38E+22
HO2	1.40E+10	4.37E+11	1.32E+13	3.64E+14	8.42E+15	1.38E+17	1.57E+18	1.36E+19	9.49E+19	4.72E+20
O3	9.95E+07	3.11E+09	9.43E+10	2.64E+12	6.14E+13	1.04E+15	1.22E+16	1.09E+17	7.70E+17	3.70E+18
NO2-	1.28E+04	7.08E+05	3.73E+07	1.72E+09	5.92E+10	1.33E+12	1.95E+13	2.15E+14	2.10E+15	1.89E+16
NO2	4.12E+08	1.26E+10	3.60E+11	8.99E+12	1.60E+14	2.18E+15	2.10E+16	1.72E+17	1.36E+18	1.01E+19
N2O	4.57E+07	1.37E+09	3.75E+10	8.18E+11	1.22E+13	1.23E+14	9.62E+14	7.27E+15	6.45E+16	7.34E+17
HNO	2.25E+09	6.90E+10	1.98E+12	4.86E+13	8.91E+14	1.13E+16	1.04E+17	8.33E+17	6.51E+18	4.99E+19
HNO2 (T)	1.60E+05	1.55E+07	1.38E+09	1.03E+11	5.33E+12	1.67E+14	3.19E+15	3.93E+16	3.04E+17	1.32E+18
HNO3	3.35E-01	1.02E+02	2.84E+04	6.43E+06	9.56E+08	7.82E+10	3.57E+12	1.06E+14	2.18E+15	2.76E+16
NH3	1.20E+07	1.15E+09	1.03E+11	7.55E+12	3.78E+14	1.12E+16	1.99E+17	2.31E+18	1.74E+19	8.09E+19
TOTAL	3.14E+18	9.90E+18	3.11E+19	9.61E+19	2.88E+20	8.20E+20	2.24E+21	5.92E+21	1.50E+22	3.84E+22

EQUILIBRIUM COMPOSITION FOR 0.99 WATER + 0.01 AIR + 7.2E-5 NACL (10,000°K)

CONCENTRATIONS IN PARTICLES/CM3

SPECIES	LOG10 OF DENSITY RATIO (STANDARD DENSITY = 1.0000E+00 GM/CM3)									
	-4.50	-4.00	-3.50	-3.00	-2.50	-2.00	-1.50	-1.00	-.50	0.00
E-	3.28E+16	5.91E+16	1.07E+17	1.92E+17	3.41E+17	5.73E+17	8.84E+17	1.22E+18	1.55E+18	1.96E+18
NA	1.53E+12	7.16E+12	3.35E+13	1.58E+14	7.24E+14	2.26E+15	9.64E+15	3.47E+16	8.91E+16	7.69E+16
NA+	7.41E+13	2.37E+14	7.25E+14	2.23E+15	6.82E+15	2.18E+16	6.30E+16	1.74E+17	3.69E+17	2.65E+17
CL-	5.51E+09	3.23E+10	1.87E+11	1.06E+12	5.87E+12	2.94E+13	1.27E+14	4.49E+14	1.30E+15	2.28E+15
CL	7.06E+13	2.30E+14	7.36E+14	2.33E+15	7.23E+15	2.16E+16	6.02E+16	1.55E+17	3.52E+17	8.89E+17
CL+	5.02E+12	9.27E+12	1.70E+13	3.11E+13	5.76E+13	1.07E+14	2.06E+14	4.06E+14	7.67E+14	8.84E+14
CL++	4.26E+05	4.56E+05	4.91E+05	5.42E+05	6.34E+05	5.96E+05	7.92E+05	1.19E+06	1.87E+06	1.79E+06
H-	1.68E+13	9.58E+13	5.45E+14	3.06E+15	1.65E+16	7.80E+16	3.02E+17	9.02E+17	1.88E+18	1.69E+18
H	2.36E+18	6.52E+18	2.06E+19	6.41E+19	1.94E+20	5.48E+20	1.37E+21	2.97E+21	4.90E+21	3.46E+21
H+	2.25E+16	4.06E+16	7.31E+16	1.32E+17	2.38E+17	4.19E+17	7.25E+17	1.28E+18	1.60E+18	9.62E+17
O-	2.45E+13	1.40E+14	7.98E+14	4.49E+15	2.44E+16	1.18E+17	4.75E+17	1.48E+18	3.19E+18	2.77E+18
O	1.03E+18	3.28E+18	1.03E+19	3.22E+19	9.88E+19	2.85E+20	7.82E+20	1.68E+21	2.85E+21	1.95E+21
O+	9.96E+15	1.79E+16	3.23E+16	5.88E+16	1.06E+17	1.91E+17	3.44E+17	5.97E+17	8.40E+17	4.76E+17
O++	7.07E+03	7.38E+03	7.82E+03	8.52E+03	9.81E+03	8.91E+03	1.11E+04	1.47E+04	1.71E+04	8.07E+03
N	1.63E+16	5.17E+16	1.62E+17	4.99E+17	1.46E+18	3.81E+18	8.58E+18	1.78E+19	2.89E+19	2.83E+19
N+	2.42E+14	4.35E+14	7.81E+14	1.39E+15	2.42E+15	3.94E+15	6.14E+15	9.32E+15	1.31E+16	1.07E+16
N++	3.04E+04	3.17E+04	3.34E+04	3.58E+04	3.94E+04	3.25E+04	3.48E+04	4.66E+04	4.73E+04	3.28E+04
NACL	2.14E+04	3.84E+05	6.71E+06	1.11E+08	1.79E+09	2.65E+10	3.07E+11	2.79E+12	2.01E+13	1.00E+14
NAO	1.01E+08	1.76E+09	3.03E+10	5.05E+11	7.86E+12	1.12E+14	1.22E+15	9.74E+15	5.21E+16	1.28E+17
HCL	2.76E+10	2.85E+11	2.88E+12	2.84E+13	2.65E+14	2.20E+15	1.50E+16	8.21E+16	3.78E+17	1.55E+18
NAH	1.14E+08	2.00E+09	3.44E+10	5.72E+11	8.83E+12	1.23E+14	1.29E+15	9.85E+15	5.11E+16	1.3[illegible]E+17
CL2	3.92E+04	4.15E+05	4.27E+06	4.27E+07	4.09E+08	3.59E+09	2.72E+10	1.77E+11	1.13E+12	5.07E+12
NA2	2.75E+00	8.37E+01	2.49E+03	7.09E+04	1.85E+06	4.61E+07	8.16E+08	1.04E+10	8.42E+10	2.62E+11
O2-	1.01E+09	1.83E+10	3.29E+11	5.74E+12	9.54E+13	1.31E+15	1.34E+16	9.32E+16	4.18E+17	1.03E+18
O2	5.83E+13	5.86E+14	5.83E+15	5.69E+16	5.28E+17	4.32E+18	2.86E+19	1.44E+20	5.10E+20	9.93E+20
O2+	6.06E+12	3.46E+13	1.97E+14	1.11E+15	6.14E+15	3.14E+16	1.43E+17	5.53E+17	1.62E+18	2.63E+18
H2	5.26E+14	5.29E+15	5.26E+16	5.11E+17	4.65E+18	3.65E+19	2.24E+20	1.03E+21	3.43E+21	7.15E+21
OH-	6.52E+09	1.18E+11	2.12E+12	3.71E+13	6.07E+14	8.18E+15	8.04E+16	5.34E+17	2.32E+18	5.94E+18
OH	4.76E+14	4.79E+15	4.76E+16	4.64E+17	4.26E+18	3.42E+19	2.18E+20	1.05E+21	3.68E+21	7.25E+21
OH+	1.48E+13	8.43E+13	4.79E+14	2.70E+15	1.48E+16	7.40E+16	3.25E+17	1.20E+18	3.41E+18	5.71E+18
N2	1.90E+12	1.91E+13	1.88E+14	1.78E+15	1.50E+16	1.01E+17	5.02E+17	1.94E+18	6.88E+18	2.76E+19
N2+	1.62E+10	9.26E+10	5.22E+11	2.85E+12	1.44E+13	6.05E+13	2.87E+14	6.13E+14	1.88E+15	5.99E+15
NO	1.50E+13	1.56E+14	1.49E+15	1.43E+16	1.26E+17	9.37E+17	5.36E+18	2.37E+19	8.38E+19	2.34E+20
NO+	8.52E+12	4.88E+13	2.75E+14	1.53E+15	8.86E+15	3.74E+16	1.48E+17	5.00E+17	1.47E+18	3.40E+18
NH	4.04E+12	4.06E+13	4.03E+14	3.85E+15	3.38E+16	2.46E+17	1.34E+18	5.72E+18	1.96E+19	5.68E+19
NAOH	1.71E+05	8.06E+06	3.77E+08	1.72E+10	7.28E+11	1.85E+13	5.29E+14	1.13E+16	1.95E+17	1.79E+18
HOCL	2.40E+05	7.86E+06	2.51E+08	7.74E+09	2.21E+11	5.36E+12	1.80E+14	1.53E+15	2.34E+16	3.46E+17
CLO2	2.70E+03	8.84E+04	2.82E+06	8.75E+07	2.52E+09	6.23E+10	1.21E+12	1.93E+13	3.05E+14	4.36E+15
H2O	5.66E+10	1.81E+12	5.68E+13	1.72E+15	4.81E+16	1.10E+18	1.86E+19	2.30E+20	6.63E+21	1.98E+22
HO2	2.09E+09	6.67E+10	2.10E+12	6.38E+13	1.80E+15	4.20E+16	7.36E+17	9.86E+18	1.13E+20	8.19E+20
O3	2.00E+07	6.37E+08	2.00E+10	6.12E+11	1.74E+13	4.15E+14	7.55E+15	1.06E+17	1.25E+18	6.76E+18
NO2-	2.64E+03	1.52E+05	8.54E+06	4.61E+08	2.22E+10	8.08E+11	1.96E+13	3.33E+14	4.96E+15	6.37E+16
NO2	2.86E+07	9.10E+08	2.84E+10	8.54E+11	2.31E+13	5.60E+14	7.80E+15	9.68E+16	1.14E+18	1.15E+19
N2O	1.95E+06	6.21E+07	1.93E+09	5.71E+10	1.48E+12	2.90E+13	3.95E+14	4.25E+15	5.80E+16	7.25E+17
HNO	2.08E+08	6.63E+09	2.07E+11	6.20E+12	1.67E+14	3.53E+15	5.34E+16	6.28E+17	7.16E+18	7.49E+19
HNO2 (T)	5.36E+03	5.41E+05	5.33E+07	4.98E+09	4.05E+11	2.40E+13	8.77E+14	1.86E+16	2.27E+17	1.28E+18
HNO3	5.87E-03	1.88E+00	5.85E+02	1.71E+05	4.25E+07	7.38E+09	7.40E+11	4.37E+13	1.77E+15	3.60E+16
NH3	2.96E+05	2.99E+07	2.95E+09	2.74E+11	2.17E+13	1.25E+15	4.22E+16	8.21E+17	9.38E+18	5.65E+19
TOTAL	3.17E+18	9.98E+18	3.14E+19	9.85E+19	3.05E+20	9.35E+20	2.63E+21	7.16E+21	1.82E+22	4.28E+22

EQUILIBRIUM COMPOSITION FOR 0.99 WATER + 0.01 AIR + 7.2E-5 NACL (12,000°K)

CONCENTRATIONS IN PARTICLES/CM3

SPECIES	LOG10 OF DENSITY RATIO (STANDARD DENSITY = 1.0000E+00 GM/CM3)									
	-4.50	-4.00	-3.50	-3.00	-2.50	-2.00	-1.50	-1.00	-.50	0.00
E-	1.41E+17	2.57E+17	4.69E+17	8.57E+17	1.56E+18	2.79E+18	4.38E+18	6.28E+18	8.10E+18	1.84E+19
NA	2.30E+12	1.06E+13	4.87E+13	2.21E+14	9.80E+14	4.08E+15	1.30E+16	4.72E+16	1.35E+17	1.41E+17
NA+	7.33E+13	2.29E+14	7.08E+14	2.17E+15	6.57E+15	1.97E+16	6.06E+16	1.71E+17	4.13E+17	3.72E+17
NA++	3.17E-01	5.70E-01	1.06E+00	2.03E+00	4.06E+00	9.08E+00	1.17E+01	2.57E+01	5.26E+01	4.09E+01
CL-	7.37E+09	4.71E+10	2.89E+11	1.72E+12	1.00E+13	5.54E+13	2.57E+14	1.02E+15	3.30E+15	6.84E+15
CL	5.87E+13	2.05E+14	6.90E+14	2.25E+15	7.19E+15	2.23E+16	6.58E+16	1.81E+17	4.56E+17	7.39E+17
CL+	1.69E+13	3.36E+13	6.48E+13	1.20E+14	2.38E+14	4.77E+14	9.57E+14	2.05E+15	4.36E+15	6.09E+15
CL++	5.50E+07	5.62E+07	6.76E+07	6.03E+07	1.02E+08	1.53E+08	1.29E+08	2.14E+08	3.86E+08	4.64E+08
CL+3	8.90E-05	6.30E-05	4.61E-05	3.64E-05	3.37E-05	4.33E-05	0.	1.22E-05	1.87E-05	1.94E-05
H-	4.56E+13	2.68E+14	1.56E+15	9.03E+15	5.11E+16	2.72E+17	1.17E+18	4.09E+18	1.06E+19	1.21E+19
H	1.98E+18	6.40E+18	2.04E+19	6.45E+19	2.00E+20	5.97E+20	1.64E+21	3.99E+21	6.01E+21	7.13E+21
H+	9.58E+16	1.75E+17	3.21E+17	5.92E+17	1.11E+18	2.14E+18	3.98E+18	7.52E+18	1.20E+19	9.82E+18
O-	5.87E+13	3.33E+14	1.94E+15	1.12E+16	6.38E+16	3.45E+17	1.53E+18	5.61E+18	1.52E+19	1.69E+19
O	1.00E+18	3.22E+18	1.03E+19	3.25E+19	1.01E+20	3.07E+20	8.68E+20	2.22E+21	4.65E+21	4.05E+21
O+	4.36E+16	7.96E+16	1.46E+17	2.69E+17	5.06E+17	9.90E+17	1.90E+18	3.77E+18	6.70E+18	5.03E+18
O++	8.86E+06	9.08E+06	1.04E+07	1.20E+07	1.49E+07	2.18E+07	1.76E+07	2.71E+07	4.07E+07	2.64E+07
N	1.54E+16	5.02E+16	1.61E+17	5.09E+17	1.57E+18	4.62E+18	1.23E+19	2.91E+19	6.04E+19	7.40E+19
N+	1.15E+15	2.09E+15	3.85E+15	7.11E+15	1.35E+16	2.52E+16	4.56E+16	8.35E+16	1.47E+17	1.55E+17
N++	1.40E+07	1.52E+07	1.68E+07	1.93E+07	2.38E+07	3.37E+07	2.56E+07	3.65E+07	5.43E+07	4.94E+07
NACL	8.77E+03	1.69E+05	3.06E+06	5.25E+07	8.38E+08	1.18E+10	1.53E+11	1.43E+12	1.04E+13	5.66E+13
NAO	5.96E+07	1.06E+09	1.82E+10	3.01E+11	4.70E+12	6.48E+13	8.01E+14	4.94E+15	4.20E+16	1.23E+17
HCL	9.86E+09	1.11E+11	1.20E+12	1.23E+13	1.22E+14	1.11E+15	8.62E+15	5.40E+16	2.76E+17	1.28E+18
NAH	7.93E+07	1.41E+09	2.42E+10	4.01E+11	6.22E+12	8.46E+13	1.01E+15	8.37E+15	4.86E+16	1.46E+17
CL2	1.62E+04	1.99E+05	2.25E+06	2.40E+07	2.44E+08	2.30E+09	1.93E+10	1.37E+11	8.79E+11	7.44E+12
NA2	1.81E+00	5.49E+01	1.60E+03	4.40E+04	1.10E+06	2.33E+07	4.82E+08	5.70E+09	4.70E+10	1.65E+11
O2-	1.04E+09	1.97E+10	3.66E+11	6.68E+12	1.18E+14	1.90E+15	2.30E+16	2.00E+17	1.15E+18	3.61E+18
O2	2.22E+13	2.30E+14	2.33E+15	2.33E+16	2.25E+17	2.03E+18	1.56E+19	9.49E+19	4.23E+20	1.04E+21
O2+	7.67E+12	4.50E+13	2.63E+14	1.53E+15	8.94E+15	5.21E+16	2.73E+17	1.29E+18	4.86E+18	1.03E+19
H2	2.28E+14	2.37E+15	2.41E+16	2.40E+17	2.30E+18	2.02E+19	1.46E+20	8.09E+20	3.30E+21	8.44E+21
OH-	6.16E+09	1.17E+11	2.17E+12	3.96E+13	6.95E+14	1.10E+16	1.29E+17	1.08E+18	5.92E+18	1.90E+19
OH	1.95E+14	2.02E+15	2.06E+16	2.05E+17	1.98E+18	1.76E+19	1.31E+20	7.61E+20	3.25E+21	8.12E+21
OH+	2.50E+13	1.47E+14	8.60E+14	5.01E+15	2.91E+16	1.67E+17	8.46E+17	3.82E+18	1.38E+19	2.97E+19
N2	2.39E+11	2.54E+12	2.61E+13	2.60E+14	2.47E+15	2.10E+16	1.44E+17	7.47E+17	3.26E+18	1.58E+19
N2+	1.47E+10	8.82E+10	5.20E+11	3.03E+12	1.74E+13	9.53E+13	4.43E+14	1.79E+15	6.61E+15	2.75E+16
NO	3.96E+12	4.13E+13	4.20E+14	4.19E+15	4.00E+16	3.50E+17	2.53E+18	1.42E+19	6.27E+19	2.16E+20
NO+	4.24E+12	2.52E+13	1.48E+14	8.67E+14	4.99E+15	2.82E+16	1.39E+17	6.07E+17	2.27E+18	6.72E+18
NH	1.95E+12	2.05E+13	2.10E+14	2.09E+15	2.00E+16	1.72E+17	1.21E+18	6.51E+18	2.75E+19	9.66E+19
NAOH	5.50E+04	2.63E+06	1.23E+08	5.57E+09	2.38E+11	8.88E+12	2.19E+14	5.42E+15	1.18E+17	1.61E+18
HOCL	5.79E+04	2.10E+06	7.14E+07	2.34E+09	7.22E+10	2.00E+12	4.59E+13	8.59E+14	1.65E+16	3.49E+17
CLO2	9.19E+02	3.33E+04	1.13E+06	3.70E+07	1.15E+09	3.22E+10	7.61E+11	1.49E+13	2.99E+14	6.20E+15
H2O	9.38E+09	3.14E+11	1.02E+13	3.21E+14	9.63E+15	2.57E+17	5.47E+18	9.06E+19	1.39E+21	1.61E+22
HO2	5.56E+08	1.86E+10	6.02E+11	1.90E+13	5.73E+14	1.55E+16	3.41E+17	5.92E+18	9.45E+19	1.08E+21
O3	6.45E+06	2.15E+08	6.96E+09	2.20E+11	6.65E+12	1.83E+14	4.14E+15	7.53E+16	1.26E+18	1.40E+19
NO2-	8.10E+02	4.97E+04	2.95E+06	1.70E+08	9.25E+09	4.40E+11	1.47E+13	3.54E+14	7.56E+15	1.52E+17
NO2	4.33E+06	1.45E+08	4.71E+09	1.49E+11	4.45E+12	1.18E+14	2.52E+15	4.23E+16	7.00E+17	1.10E+19
N2O	2.06E+05	7.60E+06	2.29E+08	7.20E+09	2.14E+11	5.53E+12	1.11E+14	1.72E+15	2.81E+16	6.20E+17
HNO	3.85E+07	1.29E+09	4.20E+10	1.32E+12	3.94E+13	1.04E+15	2.13E+16	3.42E+17	5.41E+18	4.67E+19
TOTAL	3.28E+18	1.02E+19	3.18E+19	9.97E+19	3.11E+20	9.56E+20	2.84E+21	8.05E+21	2.13E+22	4.67E+22

EQUILIBRIUM COMPOSITION FOR 0.99 WATER + 0.01 AIR + 7.2E-5 NACL (16,000°K)

CONCENTRATIONS IN PARTICLES/CM3

SPECIES	LOG10 OF DENSITY RATIO (STANDARD DENSITY = 1.0000E+00 GM/CM3)									
	-4.50	-4.00	-3.50	-3.00	-2.50	-2.00	-1.50	-1.00	-.50	0.00
E-	8.21E+17	1.61E+18	3.09E+18	5.92E+18	1.14E+19	2.25E+19	4.07E+19	6.87E+19	1.01E+20	1.32E+20
NA	3.38E+12	1.54E+13	7.01E+13	3.07E+14	1.29E+15	5.07E+15	1.87E+16	6.68E+16	2.07E+17	3.75E+17
NA+	7.23E+13	2.24E+14	6.86E+14	2.08E+15	6.27E+15	1.88E+16	5.60E+16	1.63E+17	4.65E+17	8.20E+17
NA++	6.49E+03	1.52E+04	2.86E+04	5.72E+04	1.25E+05	3.21E+05	2.87E+05	6.36E+05	1.79E+06	3.08E+06
CL-	5.15E+09	4.48E+10	3.47E+11	2.47E+12	1.67E+13	1.09E+14	6.24E+14	3.16E+15	1.31E+16	4.00E+16
CL	2.67E+13	1.19E+14	4.78E+14	1.78E+15	6.20E+15	2.05E+16	6.52E+16	1.95E+17	5.56E+17	1.29E+18
CL+	4.90E+13	1.20E+14	2.78E+14	6.10E+14	1.31E+15	2.90E+15	6.45E+15	1.58E+16	4.13E+16	9.33E+16
CL++	1.52E+10	2.16E+10	3.05E+10	4.41E+10	6.88E+10	1.31E+11	8.73E+10	1.75E+11	4.19E+11	9.24E+11
CL+3	1.18E+02	1.03E+02	9.72E+01	1.04E+02	1.39E+02	2.94E+02	2.58E+01	4.17E+01	9.14E+01	1.97E+02
H-	1.11E+14	7.78E+14	5.08E+15	3.21E+16	1.99E+17	1.22E+18	6.59E+18	3.07E+19	1.13E+20	2.38E+20
H	1.53E+18	5.51E+18	1.87E+19	6.15E+19	1.98E+20	6.17E+20	1.84E+21	5.57E+21	1.28E+22	2.05E+22
H+	5.45E+17	1.07E+18	2.06E+18	3.96E+18	7.80E+18	1.62E+19	3.36E+19	7.39E+19	1.75E+20	2.74E+20
O-	1.10E+14	7.74E+14	5.05E+15	3.19E+16	1.98E+17	1.22E+18	6.71E+18	3.24E+19	1.24E+20	2.63E+20
O	7.75E+17	2.77E+18	9.42E+18	3.10E+19	9.95E+19	3.13E+20	9.49E+20	2.71E+21	7.12E+21	1.15E+22
O+	2.70E+17	5.27E+17	1.01E+18	1.95E+18	3.85E+18	8.02E+18	1.70E+19	3.97E+19	9.57E+19	1.50E+20
O++	7.25E+10	8.18E+10	9.67E+10	1.23E+11	1.75E+11	3.14E+11	2.00E+11	3.82E+11	8.44E+11	1.29E+12
O+3	4.23E-03	2.93E-03	2.31E-03	2.17E-03	2.65E-03	5.32E-03	4.37E-04	6.83E-04	1.35E-03	2.07E-03
N	1.04E+16	3.96E+16	1.40E+17	4.71E+17	1.54E+18	4.85E+18	1.40E+19	4.10E+19	1.07E+20	2.13E+20
N+	6.17E+15	1.28E+16	2.57E+16	5.09E+16	1.02E+17	2.13E+17	4.50E+17	1.03E+18	2.47E+18	4.78E+18
N++	2.75E+10	3.31E+10	4.07E+10	5.31E+10	7.69E+10	1.39E+11	8.78E+10	1.65E+11	3.61E+11	6.83E+11
N+3	1.01E-01	7.42E-02	6.11E-02	5.88E-02	7.30E-02	1.47E-01	1.20E-02	1.85E-02	3.71E-02	6.85E-02
NACL	1.22E+03	3.15E+04	6.97E+05	1.35E+07	2.32E+08	3.45E+09	4.49E+10	4.27E+11	3.00E+12	1.79E+13
NAO	1.86E+07	3.81E+08	7.04E+09	1.20E+11	1.89E+12	2.64E+13	3.27E+14	2.97E+15	1.92E+16	7.98E+16
HCL	1.14E+09	1.65E+10	2.57E+11	3.17E+12	3.56E+13	3.65E+14	3.32E+15	2.45E+16	1.39E+17	7.36E+17
NAH	2.98E+07	6.12E+08	1.13E+10	1.93E+11	3.03E+12	4.21E+13	5.13E+14	4.49E+15	2.79E+16	1.15E+17
CL2	1.44E+03	2.95E+04	4.91E+05	6.89E+06	8.47E+07	9.26E+08	8.00E+09	7.20E+10	4.63E+11	3.54E+12
O2-	5.58E+08	1.41E+10	3.12E+11	6.44E+12	1.29E+14	2.45E+15	3.91E+16	4.80E+17	3.85E+18	1.87E+19
O2	4.27E+12	5.42E+13	6.19E+14	6.64E+15	6.79E+16	6.57E+17	5.76E+18	4.19E+19	2.30E+20	8.49E+20
O2+	7.94E+12	5.60E+13	3.65E+14	2.37E+15	1.46E+16	9.43E+16	5.80E+17	3.45E+18	1.74E+19	6.26E+19
H2	5.12E+13	6.64E+14	7.70E+15	8.34E+16	8.57E+17	9.24E+18	7.01E+19	4.75E+20	2.40E+21	8.75E+21
OH-	3.09E+09	7.79E+10	1.73E+12	3.58E+13	7.12E+14	1.35E+16	2.12E+17	2.51E+18	1.93E+19	9.31E+19
OH	3.99E+13	5.13E+14	5.90E+15	6.35E+16	6.53E+17	6.30E+18	5.44E+19	3.82E+20	2.01E+21	7.38E+21
OH+	3.38E+13	2.37E+14	1.55E+15	9.85E+15	6.21E+16	3.98E+17	2.40E+18	1.38E+19	6.66E+19	2.39E+20
N2	9.40E+09	1.36E+11	1.71E+12	1.94E+13	2.05E+14	2.02E+15	1.76E+16	1.23E+17	6.65E+17	3.73E+18
N2+	7.29E+09	5.79E+10	4.12E+11	2.75E+12	1.79E+13	1.17E+14	7.11E+14	4.07E+15	2.02E+16	1.11E+17
NO	4.36E+11	5.84E+12	6.91E+13	7.56E+14	7.82E+15	7.58E+16	6.60E+17	4.71E+18	2.56E+19	1.17E+20
NO+	1.35E+12	9.34E+12	6.37E+13	4.14E+14	2.65E+15	1.72E+16	1.05E+17	6.15E+17	3.07E+18	1.36E+19
NH	4.15E+11	5.71E+12	6.90E+13	7.67E+14	8.01E+15	7.80E+16	6.72E+17	4.63E+18	2.42E+19	1.09E+20
NAOH	7.29E+03	4.32E+05	2.24E+07	1.05E+09	4.56E+10	1.74E+12	5.69E+13	1.57E+15	3.74E+16	1.00E+18
HOCL	3.82E+03	2.19E+05	1.01E+07	4.06E+08	1.46E+10	4.69E+11	1.32E+13	3.05E+14	6.67E+15	2.29E+17
CLO2	9.34E+01	5.28E+03	2.43E+05	9.68E+06	3.46E+08	1.12E+10	3.18E+11	7.63E+12	1.74E+14	6.02E+15
H2O	5.55E+08	2.56E+10	1.00E+12	3.55E+13	1.17E+15	3.56E+16	4.37E+17	2.00E+19	3.87E+20	9.18E+21
HO2	5.84E+07	7.69E+09	1.05E+11	3.72E+12	1.23E+14	3.76E+15	1.01E+17	2.22E+18	4.44E+19	1.07E+21
O3	8.49E+05	3.95E+07	1.53E+09	5.40E+10	1.78E+12	5.44E+13	1.48E+15	3.39E+16	7.14E+17	1.72E+19
NO2-	7.52E+01	7.05E+03	5.44E+05	3.76E+07	2.42E+09	1.46E+11	7.13E+12	2.70E+14	8.26E+15	3.21E+17
NO2	1.92E+05	9.20E+06	3.69E+08	1.35E+10	4.43E+11	1.36E+13	3.67E+14	8.24E+15	1.72E+17	5.10E+18
N2O	5.12E+03	2.61E+05	1.09E+07	4.02E+08	1.36E+10	4.14E+11	1.12E+13	2.48E+14	5.14E+15	1.88E+17
HNO	2.23E+06	1.07E+08	4.31E+09	1.55E+11	5.17E+12	1.57E+14	4.18E+15	9.06E+16	1.82E+18	5.34E+19
TOTAL	3.96E+18	1.15E+19	3.45E+19	1.05E+20	3.24E+20	1.00E+21	3.04E+21	9.03E+21	2.58E+22	6.12E+22

EQUILIBRIUM COMPOSITION FOR 0.99 WATER + 0.01 AIR + 7.2E-5 NACL (20,000°K)

CONCENTRATIONS IN PARTICLES/CM3

SPECIES	LOG10 OF DENSITY RATIO	(STANDARD DENSITY = 1.0000E+00 GM/CM3)						
	-4.50	-4.00	-3.50	-3.00	-2.50	-2.00	-1.50	-1.00
E-	1.99E+18	4.25E+18	8.98E+18	1.85E+19	3.82E+19	8.15E+19	1.95E+20	3.95E+20
NA	3.47E+12	1.69E+13	7.71E+13	3.34E+14	1.36E+15	5.58E+15	1.98E+16	6.86E+16
NA+	7.22E+13	2.22E+14	6.79E+14	2.06E+15	6.20E+15	1.83E+16	5.55E+16	1.67E+17
NA++	5.07E+06	8.23E+06	1.49E+07	3.02E+07	7.01E+07	2.04E+08	1.08E+09	4.48E+08
CL-	1.92E+09	2.20E+10	2.22E+11	1.96E+12	1.56E+13	1.21E+14	9.44E+14	4.02E+15
CL	1.05E+13	5.67E+13	2.71E+14	1.16E+15	4.52E+15	1.62E+16	5.28E+16	1.47E+17
CL+	6.47E+13	1.82E+14	4.84E+14	1.25E+15	3.01E+15	7.41E+15	2.06E+16	5.64E+16
CL++	4.36E+11	6.45E+11	1.02E+12	1.73E+12	3.27E+12	7.91E+12	3.85E+13	1.35E+13
CL+3	6.34E+05	5.36E+05	5.64E+05	7.47E+05	1.38E+06	4.75E+06	8.29E+07	6.81E+05
CL+4	1.92E-04	8.51E-05	6.67E-05	8.10E-05	1.84E-04	1.31E-03	1.68E-01	0.
H-	8.76E+13	8.92E+14	7.41E+15	5.47E+16	3.82E+17	2.65E+18	1.95E+19	1.16E+20
H	8.48E+17	3.80E+18	1.49E+19	5.36E+19	1.81E+20	5.89E+20	1.81E+21	5.30E+21
H+	1.24E+18	2.77E+18	5.84E+18	1.20E+19	2.51E+19	5.53E+19	1.46E+20	3.70E+20
O-	7.19E+13	7.40E+14	6.21E+15	4.61E+16	3.24E+17	2.25E+18	1.68E+19	1.01E+20
O	4.04E+17	1.85E+18	7.39E+18	2.65E+19	9.03E+19	2.94E+20	9.12E+20	2.71E+21
O+	6.41E+17	1.45E+18	3.09E+18	6.40E+18	1.34E+19	2.97E+19	7.88E+19	2.03E+20
O++	1.60E+13	1.90E+13	2.41E+13	3.33E+13	5.39E+13	1.17E+14	5.45E+14	1.94E+14
O+3	1.64E+03	1.11E+03	9.30E+02	1.01E+03	1.60E+03	4.95E+03	8.25E+04	6.39E+02
N	4.78E+15	2.35E+16	9.95E+16	3.78E+17	1.33E+18	4.45E+18	1.40E+19	4.22E+19
N+	1.18E+16	2.89E+16	6.61E+16	1.45E+17	3.16E+17	7.18E+17	1.93E+18	5.06E+18
N++	2.33E+12	3.00E+12	4.07E+12	5.97E+12	1.00E+13	2.24E+13	1.05E+14	3.81E+13
N+3	5.35E+03	3.94E+03	3.56E+03	4.08E+03	6.69E+03	2.13E+04	3.59E+05	2.83E+03
NACL	1.39E+02	5.12E+03	1.48E+05	3.50E+06	6.89E+07	1.07E+09	1.18E+10	1.15E+11
NAO	3.57E+06	1.06E+08	2.45E+09	4.75E+10	7.97E+11	1.12E+13	1.17E+14	1.07E+15
HCL	9.45E+07	2.53E+09	5.06E+10	8.13E+11	1.11E+13	1.28E+14	1.22E+15	1.01E+16
NAH	6.42E+06	1.88E+08	4.32E+09	8.29E+10	1.38E+12	1.93E+13	2.01E+14	1.81E+15
CL2	8.57E+01	2.89E+03	7.29E+04	1.44E+06	2.31E+07	2.99E+08	3.02E+09	2.67E+10
O2-	9.11E+07	4.39E+09	1.48E+11	3.90E+12	9.55E+13	2.14E+15	8.69E+16	7.47E+17
O2	5.49E+11	1.15E+13	1.76E+14	2.24E+15	2.54E+16	2.64E+17	2.42E+18	1.90E+19
O2+	3.60E+12	3.81E+13	3.26E+14	2.46E+15	1.75E+16	1.25E+17	9.78E+17	6.68E+18
H2	7.54E+12	1.61E+14	2.54E+15	3.31E+16	3.82E+17	3.97E+18	3.59E+19	2.74E+20
OH-	5.21E+08	2.47E+10	8.24E+11	2.21E+13	5.27E+14	1.17E+16	2.56E+17	4.01E+18
OH	5.45E+12	1.13E+14	1.76E+15	2.28E+16	2.60E+17	2.71E+18	2.47E+19	1.91E+20
OH+	1.74E+13	1.82E+14	1.54E+15	1.15E+16	8.17E+16	5.79E+17	4.51E+18	3.03E+19
N2	4.62E+08	1.13E+10	2.04E+11	2.96E+12	3.68E+13	4.04E+14	3.80E+15	3.09E+16
N2+	1.78E+09	2.20E+10	2.18E+11	1.80E+12	1.42E+13	1.00E+14	8.55E+14	6.03E+15
NO	3.48E+10	8.46E+11	1.38E+13	1.85E+14	2.18E+15	2.32E+16	2.15E+17	1.72E+18
NO+	2.49E+11	3.08E+12	2.83E+13	2.26E+14	1.68E+15	1.22E+16	9.72E+16	6.75E+17
NH	5.00E+10	1.17E+12	2.00E+13	2.79E+14	3.37E+15	3.60E+16	3.33E+17	2.62E+18
NAOH	6.41E+02	6.66E+04	4.74E+06	2.65E+08	1.24E+10	5.32E+11	1.75E+13	4.99E+14
HOCL	1.73E+02	1.94E+04	1.44E+06	7.99E+07	3.57E+09	1.34E+11	4.04E+12	1.05E+14
CLO2	5.47E+00	5.98E+02	4.36E+04	2.34E+06	1.05E+08	3.95E+09	1.20E+11	3.16E+12
H2O	2.42E+07	2.37E+09	1.45E+11	6.72E+12	2.61E+14	8.84E+15	2.52E+17	6.08E+18
HO2	3.52E+06	3.35E+08	2.07E+10	9.66E+11	3.77E+13	1.28E+15	3.69E+16	9.02E+17
O3	6.04E+04	5.62E+06	3.41E+08	1.57E+10	6.05E+11	2.06E+13	5.95E+14	1.48E+16
NO2-	2.75E+00	6.16E+02	8.44E+04	8.42E+06	6.95E+08	5.18E+10	3.63E+12	1.86E+14
NO2	6.07E+03	6.06E+05	3.95E+07	1.91E+09	7.62E+10	2.66E+12	7.78E+13	1.97E+15
N2O	1.07E+02	1.15E+04	7.96E+05	4.06E+07	1.68E+09	6.01E+10	1.78E+12	4.58E+13
HNO	8.31E+04	8.70E+06	5.59E+08	2.69E+10	1.07E+12	3.71E+13	1.08E+15	2.69E+16
TOTAL	5.06E+18	1.42E+19	4.04E+19	1.18E+20	3.52E+20	1.07E+21	3.27E+21	9.78E+21

EQUILIBRIUM COMPOSITION FOR 0.99 WATER + 0.01 AIR + 7.2E-5 NACL (24,000°K)

CONCENTRATIONS IN PARTICLES/CM3

SPECIES	LOG10 OF DENSITY RATIO (STANDARD DENSITY = 1.0000E+00 GM/CM3)						
	-4.50	-4.00	-3.50	-3.00	-2.50	-2.00	-1.50
E-	2.60E+18	6.75E+18	1.61E+19	3.63E+19	8.00E+19	1.82E+20	4.82E+20
NA	2.47E+12	1.54E+13	7.37E+13	3.25E+14	1.47E+15	6.27E+15	2.15E+16
NA+	7.27E+13	2.74E+14	6.83E+14	2.07E+15	6.09E+15	1.76E+16	5.42E+16
NA++	4.51E+08	6.54E+08	1.09E+09	2.12E+09	4.88E+09	1.48E+10	9.68E+10
NA+3	7.23E-03	5.18E-03	5.30E-03	8.06E-03	1.91E-02	9.42E-02	3.10E+00
CL-	5.10E+08	8.09E+09	1.03E+11	1.10E+12	1.05E+13	9.23E+13	8.05E+14
CL	4.74E+12	2.89E+13	1.55E+14	7.31E+14	3.16E+15	1.23E+16	4.04E+16
CL+	6.65E+13	2.04E+14	5.92E+14	1.60E+15	4.36E+15	1.15E+16	3.38E+16
CL++	4.44E+12	6.30E+12	9.96E+12	1.78E+13	3.70E+13	1.02E+14	6.42E+14
CL+3	2.57E+08	1.84E+08	1.81E+08	2.51E+08	5.34E+08	2.40E+09	7.59E+10
CL+4	1.00E+01	3.98E+00	2.70E+00	3.57E+00	1.03E+01	1.16E+02	4.38E+04
H-	3.59E+13	5.42E+14	6.17E+15	5.67E+16	4.59E+17	3.55E+18	2.96E+19
H	3.75E+17	2.18E+18	1.04E+19	4.20E+19	1.56E+20	5.30E+20	1.67E+21
H+	1.70E+18	4.40E+18	1.04E+19	2.33E+19	5.12E+19	1.18E+20	3.33E+20
O-	2.45E+13	3.75E+14	4.37E+15	4.10E+16	3.57E+17	2.64E+18	2.20E+19
O	1.68E+17	9.00E+17	4.83E+18	2.01E+19	7.50E+19	2.58E+20	8.12E+20
O+	8.76E+17	2.31E+18	5.61E+18	1.29E+19	2.88E+19	6.74E+19	1.90E+20
O++	5.57E+14	6.78E+14	8.96E+14	1.32E+15	2.32E+15	5.69E+15	3.41E+16
O+3	1.92E+07	6.28E+06	5.14E+06	5.88E+06	1.06E+07	4.22E+07	1.27E+09
N	2.93E+15	1.22E+16	6.23E+16	2.72E+17	1.06E+18	3.78E+18	1.21E+19
N+	1.45E+16	4.01E+16	1.03E+17	2.51E+17	5.92E+17	1.43E+18	4.12E+18
N++	4.55E+13	5.81E+13	8.15E+13	1.28E+14	2.35E+14	5.96E+14	3.65E+15
N+3	9.77E+06	6.30E+06	5.48E+06	6.65E+06	1.26E+07	5.18E+07	1.60E+09
N+4	1.16E-05	0.	0.	0.	0.	7.60E-05	2.81E-02
O2-	6.78E+06	6.51E+08	3.84E+10	1.54E+12	4.76E+13	1.26E+15	3.16E+16
O2	5.69E+10	1.82E+12	4.04E+13	6.61E+14	8.99E+15	1.05E+17	9.90E+17
O2+	8.90E+11	1.47E+13	1.82E+14	1.78E+15	1.50E+16	1.18E+17	1.00E+18
H2	7.54E+11	2.83E+13	6.93E+14	1.21E+16	1.65E+17	1.88E+18	1.77E+19
OH-	4.44E+07	4.07E+09	2.34E+11	9.17E+12	2.78E+14	7.28E+15	1.82E+17
OH	5.52E+11	1.09E+13	4.41E+14	7.48E+15	1.02E+17	1.18E+18	1.11E+19
OH+	4.95E+12	8.01E+13	9.62E+14	9.21E+15	7.60E+16	5.95E+17	5.03E+18
N2	2.92E+07	1.09E+09	2.66E+10	5.50E+11	8.35E+12	1.04E+14	1.03E+15
N2+	3.34E+08	6.08E+09	8.44E+10	9.34E+11	8.64E+12	7.31E+13	6.47E+14
NO	3.11E+09	1.05E+11	2.50E+12	4.39E+13	6.28E+14	7.56E+15	7.30E+16
NO+	4.65E+10	8.07E+11	1.06E+13	1.10E+14	9.69E+14	7.94E+15	6.87E+16
NH	4.45E+09	1.79E+11	4.78E+12	9.09E+13	1.32E+15	1.58E+16	1.52E+17
H2O	8.35E+05	1.66E+08	1.85E+10	1.28E+12	6.42E+13	2.53E+15	7.60E+16
HO2	1.34E+05	2.70E+07	3.07E+09	2.17E+11	1.11E+13	4.40E+14	1.32E+16
O3	2.58E+03	4.86E+05	5.26E+07	3.59E+09	1.82E+11	7.34E+12	2.21E+14
NO2-	5.79E-02	2.90E+01	8.29E+03	1.34E+06	1.41E+08	1.52E+10	1.24E+12
NO2	1.55E+02	3.10E+04	3.59E+06	2.62E+08	1.40E+10	5.83E+11	1.80E+13
N2O	2.29E+00	4.68E+02	5.65E+04	4.33E+06	2.42E+08	1.04E+10	3.28E+11
HNO	2.76E+03	5.43E+05	6.16E+07	4.40E+09	2.32E+11	9.53E+12	2.93E+14
TOTAL	5.74E+18	1.67E+19	4.75E+19	1.36E+20	3.98E+20	1.17E+21	3.59E+21

EQUILIBRIUM COMPOSITION FOR 0.99 WATER + 0.01 AIR + 7.2E-5 NACL (39,810^{o}K)

CONCENTRATIONS IN PARTICLES/CM3

SPECIES	LOG10 OF DENSITY RATIO (STANDARD DENSITY = 1.0000E+00 GM/CM3)						
	-4.50	-4.00	-3.50	-3.00	-2.50	-2.00	-1.50
E-	3.44E+18	1.00E+19	2.90E+19	8.07E+19	2.09E+20	5.23E+20	1.38E+21
NA	1.37E+12	7.89E+12	4.25E+13	2.49E+14	1.49E+15	7.01E+15	2.78E+16
NA+	6.88E+13	2.24E+14	7.05E+14	2.13E+15	6.08E+15	1.69E+16	4.77E+16
NA++	5.44E+12	6.85E+12	9.01E+12	1.34E+13	2.54E+13	5.44E+13	2.06E+14
NA+3	1.18E+08	6.08E+07	5.65E+07	3.10E+07	4.31E+07	1.19E+08	1.13E+09
NA+4	3.23E-01	7.14E-02	2.18E-02	1.24E-02	1.71E-02	8.17E-02	3.69E+00
CL-	1.66E+06	6.15E+07	1.70E+09	3.99E+10	7.66E+11	1.84E+13	1.05E+14
CL	1.15E+11	1.46E+12	1.40E+13	1.18E+14	8.74E+14	4.73E+15	1.82E+16
CL+	9.86E+12	6.25E+13	3.26E+14	1.36E+15	4.65E+15	1.39E+16	3.75E+16
CL++	5.81E+13	1.66E+14	4.07E+14	9.02E+14	2.02E+15	5.21E+15	1.91E+16
CL+3	7.58E+12	8.91E+12	1.01E+13	1.28E+13	2.25E+13	6.99E+13	6.47E+14
CL+4	1.04E+10	5.28E+09	3.01E+09	2.56E+09	4.48E+09	2.41E+10	1.06E+12
CL+5	8.49E+03	2.05E+03	4.52E+03	4.33E+03	9.53E+03	1.24E+05	4.98E+07
H-	1.80E+12	3.33E+13	6.01E+14	1.01E+16	1.38E+17	1.50E+18	1.45E+19
H	5.95E+16	3.79E+17	2.37E+18	1.43E+19	7.55E+19	3.27E+20	1.20E+21
H+	2.02E+18	6.20E+18	1.84E+19	5.14E+19	1.32E+20	3.29E+20	8.64E+20
O-	4.93E+11	1.14E+13	2.25E+14	4.00E+15	3.79E+16	6.59E+17	6.51E+18
O	1.59E+16	1.27E+17	8.63E+17	5.51E+18	3.08E+19	1.40E+20	5.24E+20
O+	6.47E+17	2.58E+18	8.73E+18	2.63E+19	7.14E+19	1.85E+20	4.97E+20
O++	3.81E+17	5.95E+17	8.50E+17	1.26E+18	2.13E+18	4.61E+18	1.66E+19
O+3	3.40E+14	2.19E+14	1.44E+14	1.27E+14	1.67E+14	4.21E+14	3.81E+15
O+4	1.79E+08	4.92E+07	1.63E+07	9.26E+06	1.22E+07	5.49E+07	2.35E+09
O+5	1.71E-02	2.14E-03	3.95E-04	1.75E-04	2.91E-04	3.27E-03	1.24E+00
N	1.68E+14	1.53E+15	1.13E+16	7.54E+16	4.30E+17	2.03E+18	7.74E+18
N+	7.48E+15	3.45E+16	1.28E+17	4.08E+17	1.15E+18	3.05E+18	8.25E+18
N++	4.89E+15	1.63E+16	2.59E+16	4.09E+16	7.19E+16	1.59E+17	5.80E+17
N+3	2.95E+13	2.21E+13	1.61E+13	1.46E+13	2.01E+13	5.35E+13	4.90E+14
N+4	9.08E+07	2.97E+07	1.08E+07	6.50E+06	8.92E+06	4.11E+07	1.78E+09
N+5	2.68E-01	3.93E-02	8.08E-03	3.88E-03	6.56E-03	7.56E-02	2.91E+01
TOTAL	6.60E+18	2.08E+19	6.05E+19	1.80E+20	5.23E+20	1.52E+21	4.52E+21

EQUILIBRIUM COMPOSITION FOR 0.99 WATER + 0.01 AIR + 7.2E-5 NACL (63,095°K)

CONCENTRATIONS IN PARTICLES/CM3

SPECIES	LOG10 OF DENSITY RATIO (STANDARD DENSITY = 1.0000E+00 GM/CM3)							
	-4.50	-4.00	-3.50	-3.00	-2.50	-2.00	-1.50	-1.00
E-	4.46E+18	1.32E+19	5.90E+19	1.12E+20	3.06E+20	7.94E+20	2.04E+21	6.35E+21
NA	4.07E+10	5.64E+11	6.17E+12	7.42E+13	6.98E+14	4.67E+15	2.31E+16	7.96E+16
NA+	6.31E+12	4.33E+13	2.57E+14	1.23E+15	4.69E+15	1.48E+16	4.19E+16	1.10E+17
NA++	6.45E+13	1.90E+14	4.87E+14	1.08E+15	2.17E+15	4.43E+15	1.06E+16	4.94E+16
NA+3	4.75E+12	5.26E+12	5.50E+12	5.71E+12	6.71E+12	1.09E+13	3.25E+13	6.37E+14
NA+4	9.36E+08	4.05E+08	1.82E+08	9.78E+07	7.85E+07	1.28E+08	7.06E+08	1.37E+11
NA+5	8.79E+01	1.54E+01	3.16E+00	9.73E-01	6.23E-01	1.31E+00	1.95E+01	8.82E+04
CL-	9.20E+02	1.01E+05	5.46E+06	3.30E+08	1.57E+10	4.31E+11	6.55E+12	2.14E+13
CL	2.42E+08	4.02E+09	1.64E+11	3.51E+12	6.03E+13	6.37E+14	3.76E+15	3.95E+15
CL+	1.63E+11	2.80E+12	3.23E+13	2.51E+14	1.36E+15	5.45E+15	1.83E+16	1.47E+16
CL++	7.01E+12	5.49E+13	3.02E+14	1.27E+15	4.31E+15	1.32E+16	3.63E+16	5.04E+16
CL+3	4.29E+13	1.47E+14	3.82E+14	8.27E+14	1.76E+15	4.47E+15	1.59E+16	9.47E+16
CL+4	2.51E+13	3.47E+13	3.95E+13	4.49E+13	6.58E+13	1.70E+14	1.12E+15	6.60E+16
CL+5	5.15E+11	2.88E+11	1.51E+11	9.80E+10	1.15E+11	3.80E+11	6.79E+12	9.35E+15
H-	2.12E+11	3.76E+12	6.69E+13	1.38E+15	2.45E+16	3.37E+17	3.78E+18	4.22E+19
H	2.61E+16	1.56E+17	9.41E+17	6.77E+18	4.00E+19	2.33E+20	1.01E+21	3.64E+21
H+	2.05E+18	6.42E+18	1.99E+19	5.90E+19	1.64E+20	4.25E+20	1.06E+21	2.87E+21
O-	1.32E+09	6.94E+10	2.72E+12	1.09E+14	3.13E+15	5.85E+16	7.58E+17	7.41E+18
O	2.45E+14	4.36E+15	5.78E+16	8.05E+17	8.48E+18	6.11E+19	3.07E+20	9.93E+20
O+	4.72E+16	3.79E+17	2.48E+18	1.30E+19	5.34E+19	1.74E+20	5.09E+20	1.25E+21
O++	6.78E+17	2.47E+18	7.36E+18	1.86E+19	4.18E+19	9.15E+19	2.23E+20	9.73E+20
O+3	3.18E+17	4.44E+17	5.41E+17	6.45E+17	8.49E+17	1.48E+18	4.51E+18	8.28E+19
O+4	1.24E+15	6.76E+14	3.56E+14	2.19E+14	1.97E+14	3.47E+14	1.95E+15	3.54E+17
O+5	2.32E+10	5.10E+09	1.23E+09	4.34E+08	3.11E+08	7.01E+08	1.07E+10	4.53E+13
O+6	1.92E+03	1.76E+02	2.07E+01	4.61E+00	3.08E+00	1.13E+01	6.93E+02	1.61E+08
N	2.11E+12	4.31E+13	6.14E+14	9.23E+15	1.05E+17	8.04E+17	4.18E+18	1.28E+19
N+	4.98E+14	4.46E+15	3.15E+16	1.70E+17	7.51E+17	2.59E+18	7.71E+18	1.78E+19
N++	8.30E+15	3.53E+16	1.16E+17	3.18E+17	7.69E+17	1.79E+18	4.49E+18	1.85E+19
N+3	7.60E+15	1.25E+16	1.71E+16	2.22E+16	3.14E+16	5.85E+16	1.84E+17	3.20E+18
N+4	9.32E+13	5.96E+13	3.51E+13	2.36E+13	2.29E+13	4.29E+13	2.48E+14	4.27E+16
N+5	1.07E+10	2.77E+09	7.49E+08	2.88E+08	2.23E+08	5.35E+08	6.42E+09	3.37E+13
TOTAL	7.60E+18	2.31E+19	7.04E+19	2.11E+20	6.20E+20	1.79E+21	5.16E+21	1.63E+22

EQUILIBRIUM COMPOSITION FOR 0.99 WATER + 0.01 AIR + 7.2E-5 NACL (99,999^{o}K)

CONCENTRATIONS IN PARTICLES/CM3

SPECIES	LOG10 OF DENSITY RATIO (STANDARD DENSITY = 1.0000E+00 GM/CM3)							
	-4.50	-4.00	-3.50	-3.00	-2.50	-2.00	-1.50	-1.00
E-	5.81E+18	1.72E+19	5.06E+19	1.47E+20	4.19E+20	1.15E+21	3.06E+21	9.48E+21
NA	7.67E+07	2.56E+09	4.06E+10	1.42E+12	3.25E+13	4.74E+14	4.17E+15	1.88E+16
NA+	9.74E+10	1.58E+12	1.91E+13	1.69E+14	1.08E+15	5.64E+15	2.44E+16	6.50E+16
NA++	6.04E+12	4.80E+13	2.84E+14	1.30E+15	4.77E+15	1.44E+16	3.06E+16	1.13E+17
NA+3	5.39E+13	1.72E+14	4.35E+14	9.00E+14	1.67E+15	3.18E+15	7.45E+15	4.17E+16
NA+4	1.52E+13	1.81E+13	1.82E+13	1.68E+13	1.66E+13	2.24E+13	5.81E+13	1.16E+15
NA+5	3.16E+10	1.43E+10	5.94E+09	2.58E+09	1.50E+09	1.70E+09	6.37E+09	8.28E+11
CL-	1.99E-02	8.41E+00	8.55E+02	2.95E+05	5.11E+07	4.09E+09	1.29E+11	3.13E+11
CL	1.26E+04	1.80E+06	6.21E+07	7.36E+09	4.49E+11	1.31E+13	1.55E+14	1.21E+14
CL+	5.02E+07	3.56E+09	1.54E+11	3.86E+12	4.76E+13	3.59E+14	2.09E+15	9.64E+14
CL++	2.07E+10	5.65E+11	1.04E+13	1.21E+14	9.83E+14	4.15E+15	1.18E+16	5.48E+15
CL+3	1.65E+12	1.78E+13	1.40E+14	7.73E+14	3.15E+15	1.04E+16	2.91E+16	2.55E+16
CL+4	2.17E+13	1.08E+14	4.12E+14	1.21E+15	3.04E+15	8.02E+15	2.74E+16	9.32E+16
CL+5	5.23E+13	1.13E+14	1.94E+14	2.86E+14	4.43E+14	1.01E+15	5.06E+15	1.14E+17
H-	3.56E+10	6.15E+11	1.07E+13	2.59E+14	5.46E+15	9.28E+16	1.24E+18	1.57E+19
H	1.38E+16	8.09E+16	4.79E+17	3.98E+18	2.95E+19	1.82E+20	9.11E+20	3.74E+21
H+	2.07E+18	6.50E+18	2.03E+19	6.18E+19	1.79E+20	4.75E+20	1.17E+21	2.82E+21
O-	3.36E+05	5.06E+07	3.78E+09	4.78E+11	3.68E+13	1.63E+15	3.99E+16	5.05E+17
O	2.93E+11	1.49E+13	3.78E+14	1.65E+16	4.45E+17	7.19E+18	6.60E+19	2.70E+20
O+	3.71E+14	8.64E+15	1.37E+17	1.49E+18	1.12E+19	6.42E+19	2.90E+20	6.99E+20
O++	3.45E+16	3.43E+17	2.48E+18	1.33E+19	5.49E+19	1.80E+20	4.96E+20	1.27E+21
O+3	4.49E+17	2.01E+18	6.58E+18	1.68E+19	3.63E+19	7.64E+19	1.86E+20	9.40E+20
O+4	5.58E+17	9.28E+17	1.23E+18	1.41E+18	1.69E+18	2.47E+18	6.67E+18	1.21E+20
O+5	2.28E+16	1.50E+16	8.20E+15	4.44E+15	3.05E+15	3.83E+15	1.50E+16	1.76E+18
O+6	2.32E+13	5.93E+12	1.39E+12	3.78E+11	1.70E+11	2.11E+11	1.56E+12	2.18E+15
N	2.07E+09	1.25E+11	3.53E+12	1.73E+14	5.14E+15	8.91E+16	8.54E+17	3.24E+18
N+	2.88E+12	7.98E+13	1.46E+15	1.76E+16	1.41E+17	8.53E+17	4.02E+18	8.99E+18
N++	3.24E+14	3.73E+15	3.04E+16	1.78E+17	7.84E+17	2.70E+18	7.63E+18	1.81E+19
N+3	5.12E+15	2.08E+16	1.01E+17	2.85E+17	6.73E+17	1.51E+18	3.82E+18	1.79E+19
N+4	1.02E+16	2.10E+16	3.26E+16	4.21E+16	5.37E+16	8.65E+16	2.44E+17	4.09E+18
N+5	9.42E+14	7.43E+14	4.75E+14	2.90E+14	2.19E+14	2.95E+14	1.20E+15	1.31E+17
TOTAL	8.95E+18	2.71E+19	8.21E+19	2.47E+20	7.33E+20	2.14E+21	6.21E+21	1.94E+22

EQUILIBRIUM COMPOSITION FOR 0.99 WATER + 0.01 AIR + 7.2E-5 NACL (158,489°K)

CONCENTRATIONS IN PARTICLES/CM3

SPECIES	LOG10 OF DENSITY RATIO (STANDARD DENSITY = 1.0000E+00 GM/CM3)								
	-4.50	-4.00	-3.50	-3.00	-2.50	-2.00	-1.50	-1.00	-.50
E-	7.46E+18	2.23E+19	6.58E+19	1.92E+20	5.56E+20	1.58E+21	4.44E+21	1.40E+22	7.26E+22
NA	5.86E+03	6.45E+05	1.55E+07	1.96E+09	1.47E+11	6.13E+12	1.31E+14	8.79E+14	5.63E+09
NA+	4.53E+07	2.85E+09	1.14E+11	2.76E+12	3.61E+13	4.30E+14	4.00E+15	1.32E+16	8.81E+10
NA++	2.67E+10	6.45E+11	1.08E+13	1.26E+14	1.01E+15	5.65E+15	2.23E+16	5.55E+16	2.10E+12
NA+3	2.29E+12	2.25E+13	1.65E+14	9.01E+14	3.74E+15	1.24E+16	3.61E+16	9.96E+16	1.18E+14
NA+4	3.25E+13	1.47E+14	4.90E+14	1.26E+15	2.67E+15	5.31E+15	1.28E+16	6.58E+16	1.27E+16
NA+5	4.08E+13	6.94E+13	9.13E+13	1.01E+14	1.05E+14	1.31E+14	2.99E+14	4.25E+15	7.44E+17
CL	6.11E-01	1.17E+02	5.83E+03	1.82E+06	3.46E+08	3.23E+10	1.04E+12	2.30E+12	3.32E+05
CL+	1.08E+04	1.15E+06	9.53E+07	5.13E+09	1.23E+11	2.41E+12	3.35E+13	3.71E+13	5.48E+06
CL++	2.64E+07	1.05E+09	3.43E+10	8.48E+11	1.38E+13	1.27E+14	4.42E+14	3.69E+14	3.09E+08
CL+3	2.95E+10	4.18E+11	5.18E+12	5.23E+13	3.94E+14	1.99E+15	5.63E+15	2.99E+15	7.67E+10
CL+4	5.95E+12	3.18E+13	1.69E+14	7.27E+14	2.90E+15	9.93E+15	2.87E+16	4.01E+16	1.51E+14
CL+5	6.97E+13	2.07E+14	5.91E+14	1.61E+15	4.26E+15	1.19E+16	4.08E+16	1.96E+17	7.56E+17
H-	7.68E+09	1.33E+11	2.57E+12	6.90E+13	1.51E+15	2.98E+16	4.79E+17	6.94E+18	1.11E+20
H	7.65E+15	4.44E+16	2.90E+17	2.51E+18	2.01E+19	1.40E+20	8.02E+20	3.69E+21	1.14E+22
H+	2.07E+18	6.53E+18	2.05E+19	6.33E+19	1.88E+20	5.17E+20	1.28E+21	2.88E+21	9.29E+21
O-	3.81E+00	2.35E+03	4.92E+05	2.48E+08	6.67E+10	9.04E+12	5.84E+14	1.10E+16	2.95E+08
O	1.20E+07	2.48E+09	1.75E+11	3.02E+13	2.79E+15	1.34E+17	3.09E+18	1.84E+19	9.54E+10
O+	8.33E+10	9.12E+12	5.08E+14	1.90E+16	3.14E+17	4.41E+18	4.39E+19	1.28E+20	6.93E+11
O++	6.05E+13	2.49E+15	6.31E+16	9.73E+17	9.29E+18	5.68E+19	2.31E+20	5.07E+20	1.55E+13
O+3	7.03E+15	1.15E+17	1.23E+18	8.78E+18	4.31E+19	1.59E+20	4.85E+20	1.16E+21	1.09E+15
O+4	1.50E+17	1.07E+18	5.21E+18	1.76E+19	4.46E+19	1.00E+20	2.57E+20	1.16E+21	1.80E+17
O+5	6.34E+17	1.84E+18	3.71E+18	5.55E+18	7.10E+18	1.02E+19	2.50E+19	3.15E+20	4.05E+19
O+6	2.50E+17	2.76E+17	2.22E+17	1.47E+17	9.85E+16	9.85E+16	2.80E+17	1.50E+19	1.04E+22
N	1.81E+05	3.15E+07	2.26E+09	4.00E+11	3.88E+13	1.95E+15	4.61E+16	2.65E+17	2.56E+11
N+	1.27E+09	1.16E+11	6.94E+12	2.38E+14	4.10E+15	6.01E+16	6.14E+17	1.73E+18	1.74E+12
N++	9.87E+11	3.36E+13	8.17E+14	1.28E+16	1.27E+17	7.98E+17	3.28E+18	6.96E+18	3.97E+13
N+3	1.30E+14	1.73E+15	1.76E+16	1.27E+17	6.39E+17	2.42E+18	7.50E+18	1.71E+19	3.00E+15
N+4	3.02E+15	1.77E+16	8.24E+16	2.84E+17	7.51E+17	1.76E+18	4.61E+18	2.01E+19	5.81E+17
N+5	1.34E+16	3.29E+16	6.48E+16	1.00E+17	1.35E+17	2.03E+17	5.15E+17	6.27E+18	1.65E+20
N+6	3.51E+03	3.17E+03	2.46E+03	1.68E+03	1.18E+03	1.23E+03	3.60E+03	1.86E+05	2.41E+10
TOTAL	1.06E+19	3.22E+19	9.72E+19	2.92E+20	8.70E+20	2.57E+21	7.58E+21	2.39E+22	1.04E+23

EQUILIBRIUM COMPOSITION FOR 0.99 WATER + 0.01 AIR + 7.2E-5 NACL (251,188°K)

CONCENTRATIONS IN PARTICLES/CM3

SPECIES	LOG10 OF DENSITY RATIO (STANDARD DENSITY = 1.0000E+00 GM/CM3)									
	-4.50	-4.00	-3.50	-3.00	-2.50	-2.00	-1.50	-1.00	-.50	0.00
E-	8.32E+18	2.59E+19	7.97E+19	2.40E+20	7.08E+20	2.06E+21	5.92E+21	1.78E+22	6.80E+22	2.20E+23
NA	6.68E-02	1.44E+01	4.85E+02	2.12E+05	5.88E+07	8.98E+09	6.41E+11	1.33E+13	2.47E+12	4.83E+08
NA+	3.79E+03	5.11E+05	5.29E+07	3.40E+09	6.70E+10	2.68E+12	7.56E+13	6.74E+14	6.52E+13	1.13E+10
NA++	1.15E+07	5.55E+08	2.27E+10	7.21E+11	1.38E+13	2.12E+14	1.89E+15	9.28E+15	9.39E+14	4.07E+11
NA+3	1.77E+10	2.86E+11	4.11E+12	4.87E+13	4.36E+14	2.75E+15	1.14E+16	2.87E+16	6.07E+15	1.88E+13
NA+4	3.57E+12	2.13E+13	1.23E+14	6.54E+14	3.00E+15	1.16E+16	3.86E+16	1.12E+17	9.48E+16	5.96E+15
NA+5	7.20E+13	2.18E+14	6.29E+14	1.69E+15	4.11E+15	9.38E+15	2.36E+16	8.88E+16	6.54E+17	2.39E+18
CL	1.93E-04	4.34E-02	2.53E+00	1.22E+03	4.08E+05	8.19E+07	7.58E+09	1.54E+11	1.38E+10	2.37E+06
CL+	1.25E+01	1.71E+03	1.84E+05	1.29E+07	2.82E+08	1.42E+10	5.19E+11	4.52E+12	2.11E+11	3.19E+07
CL++	1.33E+05	6.30E+06	2.57E+08	8.26E+09	1.86E+11	2.32E+12	1.50E+13	7.22E+13	3.52E+12	1.34E+09
CL+3	1.18E+09	1.89E+10	2.70E+11	3.30E+12	3.19E+13	2.17E+14	7.69E+14	8.07E+14	8.23E+13	2.23E+11
CL+4	2.98E+12	1.62E+13	8.37E+13	3.98E+14	1.69E+15	6.18E+15	1.77E+16	2.76E+16	7.39E+15	4.07E+14
CL+5	7.27E+13	2.23E+14	6.72E+14	1.99E+15	5.84E+15	1.75E+16	5.72E+16	2.11E+17	7.49E+17	2.39E+18
H-	1.61E+09	2.98E+10	6.62E+11	1.82E+13	4.59E+14	1.02E+16	1.90E+17	2.96E+18	4.63E+19	4.90E+20
H	3.98E+15	2.36E+16	1.71E+17	1.56E+18	1.33E+19	1.02E+20	6.61E+20	3.42E+21	1.40E+22	4.59E+22
H+	2.09E+18	6.55E+18	2.06E+19	6.42E+19	1.95E+20	5.55E+20	1.42E+21	3.15E+21	6.74E+21	1.94E+22
O	4.70E+01	2.97E+04	6.28E+06	5.20E+09	2.14E+12	3.98E+14	3.03E+16	6.01E+17	2.23E+16	2.82E+10
O+	1.77E+06	6.55E+08	1.62E+11	2.04E+13	7.48E+14	4.03E+16	1.21E+18	1.03E+19	2.00E+17	2.23E+11
O++	8.20E+09	1.06E+12	1.00E+14	5.76E+15	1.75E+17	2.52E+18	2.05E+19	9.62E+19	1.95E+18	5.46E+12
O+3	6.49E+12	3.79E+14	1.31E+16	3.04E+17	4.27E+18	3.53E+19	1.75E+20	4.65E+20	1.97E+19	3.93E+14
O+4	2.04E+15	3.25E+16	4.30E+17	4.19E+18	2.77E+19	1.26E+20	4.37E+20	1.18E+21	1.98E+20	8.07E+16
O+5	9.79E+16	6.23E+17	3.51E+18	1.56E+19	5.16E+19	1.35E+20	3.47E+20	1.21E+21	1.74E+21	4.10E+19
O+6	9.44E+17	2.65E+18	6.49E+18	1.29E+19	2.07E+19	3.12E+19	6.32E+19	3.44E+20	8.48E+21	3.30E+22
O+7	2.22E+08	2.14E+08	1.92E+08	1.54E+08	1.15E+08	1.01E+08	1.76E+08	1.87E+09	1.54E+12	2.81E+15
O+8	2.96E-09	0.	0.	0.	0.	0.	0.	1.00E-05	5.50E-01	1.34E+06
N	3.05E+01	7.20E+03	7.56E+05	3.30E+08	9.01E+10	1.34E+13	9.17E+14	1.88E+16	3.82E+15	7.54E+11
N+	1.01E+06	1.37E+08	1.45E+10	9.75E+11	2.55E+13	1.12E+15	3.04E+16	2.68E+17	2.84E+16	4.94E+12
N++	4.28E+09	2.03E+11	8.18E+12	2.50E+14	5.12E+15	6.02E+16	4.55E+17	2.21E+18	2.45E+17	1.07E+14
N+3	4.06E+12	6.67E+13	9.85E+14	1.22E+16	1.15E+17	7.70E+17	3.50E+18	9.80E+18	2.27E+18	7.07E+15
N+4	7.84E+14	4.69E+15	2.71E+16	1.44E+17	6.52E+17	2.44E+18	7.84E+18	2.25E+19	2.09E+19	1.32E+18
N+5	1.58E+16	4.76E+16	1.38E+17	3.68E+17	8.84E+17	1.96E+18	4.74E+18	1.76E+19	1.42E+20	5.23E+20
N+6	2.09E+10	2.15E+10	2.24E+10	2.35E+10	2.51E+10	3.01E+10	5.48E+10	3.09E+11	4.16E+13	2.52E+16
N+7	3.46E+01	1.23E+01	4.67E+00	1.97E+00	9.81E-01	6.85E-01	1.07E+00	1.18E+01	5.31E+04	1.51E+10
TOTAL	1.15E+19	3.59E+19	1.11E+20	3.39E+20	1.02E+21	3.05E+21	9.06E+21	2.77E+22	9.94E+22	3.19E+23

EQUILIBRIUM COMPOSITION FOR 0.99 WATER + 0.01 AIR + 7.2E-5 NACL (398,1070°K)

CONCENTRATIONS IN PARTICLES/CM3

SPECIES	LOG10 OF DENSITY RATIO (STANDARD DENSITY = 1.0000E+00 GM/CM3)										
	-4.50	-4.00	-3.50	-3.00	-2.50	-2.00	-1.50	-1.00	-.50	0.00	.50
E-	8.40E+18	2.64E+19	8.30E+19	2.59E+20	7.96E+20	2.40E+21	7.05E+21	2.06E+22	6.31E+22	2.11E+23	6.70E+23
NA	0.	1.45E-03	3.39E-02	2.38E+01	1.29E+04	4.73E+06	9.89E+08	8.97E+10	1.56E+12	6.35E+11	7.68E+08
NA+	1.92E+00	2.91E+02	3.74E+04	3.29E+06	3.61E+07	4.60E+09	3.53E+11	1.26E+13	9.28E+13	1.95E+13	1.86E+10
NA++	2.84E+04	1.48E+06	7.14E+07	2.96E+09	9.46E+10	1.89E+12	3.27E+13	5.23E+14	2.14E+15	4.04E+14	7.50E+11
NA+3	4.30E+08	7.31E+09	1.18E+11	1.70E+12	2.05E+13	1.84E+14	9.59E+14	3.39E+15	1.00E+16	2.94E+15	2.65E+13
NA+4	1.52E+12	8.59E+12	4.72E+13	2.47E+14	1.20E+15	5.13E+15	1.87E+16	5.24E+16	1.16E+17	9.13E+16	9.97E+15
NA+5	7.41E+13	2.31E+14	7.09E+14	2.14E+15	6.35E+15	1.86E+16	5.59E+16	1.83E+17	6.28E+17	2.30E+18	7.55E+18
CL-	0.	0.	0.	1.27E-05	2.15E-02	2.45E+01	1.59E+04	4.47E+06	2.34E+08	2.83E+08	1.05E+06
CL	0.	5.58E-05	3.20E-03	2.26E+00	1.24E+03	4.71E+05	1.04E+08	1.00E+10	1.71E+11	6.18E+10	7.24E+07
CL+	4.60E-02	7.00E+00	9.06E+02	8.17E+04	1.37E+06	1.60E+08	1.45E+10	5.50E+11	3.99E+12	7.45E+11	6.85E+08
CL++	1.71E+03	8.84E+04	4.18E+06	1.68E+08	5.03E+09	7.94E+10	8.71E+11	1.48E+13	5.95E+13	9.96E+12	1.79E+10
CL+3	7.86E+07	1.33E+09	2.13E+10	3.06E+11	3.64E+12	3.16E+13	1.40E+14	2.45E+14	7.13E+14	1.85E+14	1.62E+12
CL+4	1.50E+12	8.34E+12	4.50E+13	2.29E+14	1.06E+15	4.20E+15	1.31E+16	2.19E+16	2.49E+16	1.74E+16	1.84E+15
CL+5	7.41E+13	2.31E+14	7.11E+14	2.16E+15	6.50E+15	1.97E+16	6.24E+16	2.17E+17	7.31E+17	2.37E+18	7.56E+18
H-	3.28E+08	6.15E+09	1.45E+11	4.33E+12	1.23E+14	3.15E+15	6.79E+16	1.17E+18	1.68E+19	2.14E+20	2.23E+21
H	1.98E+15	1.18E+16	8.81E+16	8.47E+17	7.82E+18	6.65E+19	4.88E+20	2.88E+21	1.35E+22	5.12E+22	1.69E+23
H+	2.08E+18	6.57E+18	2.07E+19	6.49E+19	2.00E+20	5.91E+20	1.59E+21	3.69E+21	7.33E+21	1.48E+22	3.73E+22
O-	0.	0.	8.01E-05	4.66E-01	1.80E+03	3.66E+06	3.18E+09	9.29E+11	4.27E+13	1.19E+13	6.48E+08
O	1.47E-03	1.11E+00	2.51E+02	4.68E+05	5.86E+08	3.97E+11	1.17E+14	1.17E+16	1.74E+17	1.47E+16	2.51E+11
O+	2.39E+02	1.10E+05	4.12E+07	9.97E+09	4.61E+11	1.08E+14	1.18E+16	4.61E+17	2.91E+18	1.27E+17	1.70E+12
O++	5.92E+06	9.26E+08	1.27E+11	1.37E+13	9.59E+14	3.00E+16	5.66E+17	9.98E+18	3.49E+19	1.36E+18	3.58E+13
O+3	3.89E+10	2.07E+12	9.51E+13	3.76E+15	1.10E+17	2.00E+18	1.90E+19	1.10E+20	2.78E+20	1.69E+19	2.15E+15
O+4	7.31E+13	1.26E+15	2.04E+16	2.95E+17	3.47E+18	2.99E+19	1.74E+20	6.52E+20	1.37E+21	2.22E+20	3.44E+17
O+5	3.29E+16	1.98E+17	1.13E+16	6.34E+18	3.19E+19	1.35E+20	4.77E+20	1.49E+21	3.88E+21	2.90E+21	1.37E+20
O+6	1.01E+18	5.11E+18	9.29E+18	2.64E+19	6.89E+19	1.63E+20	3.74E+20	1.04E+21	4.88E+21	2.98E+22	1.04E+23
O+7	1.34E+14	1.35E+14	1.37E+14	1.40E+14	1.44E+14	1.55E+14	2.07E+14	5.10E+14	5.00E+15	4.27E+17	2.78E+20
O+8	9.49E+07	3.17E+07	1.10E+07	4.09E+06	1.69E+06	8.74E+05	7.35E+05	1.83E+06	4.90E+07	1.01E+11	3.06E+16
N	2.63E-02	6.89E+00	6.84E+02	4.72E+05	2.46E+08	8.25E+10	1.50E+13	1.16E+15	2.09E+16	1.17E+16	1.45E+13
N+	3.35E+03	5.21E+05	6.80E+07	6.20E+09	1.47E+11	1.72E+13	1.15E+15	3.49E+16	2.67E+17	7.72E+16	7.48E+13
N++	6.51E+07	3.45E+09	1.65E+11	6.64E+12	1.97E+14	3.28E+15	4.33E+16	5.93E+17	2.51E+18	6.51E+17	1.23E+15
N+3	3.16E+11	5.55E+12	9.15E+13	1.36E+15	1.70E+16	1.61E+17	1.03E+18	5.13E+18	1.57E+19	6.32E+18	5.82E+16
N+4	3.40E+14	2.02E+15	1.17E+16	6.57E+16	3.43E+17	1.60E+18	6.39E+18	2.12E+19	5.68E+19	6.14E+19	6.84E+18
N+5	1.57E+16	4.99E+16	1.53E+17	4.56E+17	1.30E+18	3.48E+18	9.10E+18	2.55E+19	9.04E+19	4.55E+20	1.53E+21
N+6	4.85E+14	5.03E+14	5.21E+14	5.47E+14	5.94E+14	6.95E+14	9.82E+14	2.12E+15	1.21E+16	4.90E+17	1.23E+20
N+7	1.32E+11	4.51E+10	1.58E+10	5.96E+09	2.54E+09	1.36E+09	1.12E+09	2.14E+09	2.54E+10	1.44E+13	6.76E+17
TOTAL	1.15E+19	3.64E+19	1.14E+20	3.58E+20	1.11E+21	3.39E+21	1.02E+22	3.05E+22	9.45E+22	3.11E+23	9.84E+23

EQUILIBRIUM COMPOSITOIN FOR 0.99 WATER + 0.01 AIR + 7.2E-5 NACL (630,957OK)

CONCENTRATIONS IN PARTICLES/CM3

SPECIES	LOG10 OF DENSITY RATIO (STANDARD DENSITY = 1.0000E+00 GM/CM3)										
	-4.50	-4.00	-3.50	-3.00	-2.50	-2.00	-1.50	-1.00	-.50	0.00	.50
E-	8.87E+18	2.72E+19	8.46E+19	2.64E+20	8.23E+20	2.54E+21	7.66E+21	2.26E+22	6.54E+22	1.97E+23	6.51E+23
NA	0.	0.	1.43E-05	1.16E-02	8.44E+00	4.94E+03	2.04E+06	5.09E+08	5.09E+10	1.21E+12	1.24E+12
NA+	4.89E-03	7.04E+01	9.29E+01	9.09E+03	6.99E+04	1.36E+07	1.95E+09	1.77E+11	6.92E+12	6.89E+13	3.44E+13
NA++	2.89E+02	1.45E+04	7.11E+05	3.20E+07	1.17E+09	2.55E+10	5.60E+11	1.99E+13	3.46E+14	1.82E+15	7.16E+14
NA+3	2.48E+07	4.10E+08	6.81E+09	1.06E+11	1.45E+12	1.55E+13	8.85E+13	3.23E+14	2.82E+15	9.93E+15	4.95E+15
NA+4	7.70E+11	4.28E+12	2.35E+13	1.25E+14	6.25E+14	2.78E+15	1.00E+16	2.20E+16	5.94E+16	1.77E+17	1.81E+17
NA+5	7.49E+13	2.35E+14	7.33E+14	2.27E+15	6.94E+15	2.11E+16	6.55E+16	2.17E+17	4.94E+17	2.20E+18	7.38E+18
CL-	0.	0.	0.	0.	5.86E-05	1.06E-01	1.34E+02	1.00E+05	2.96E+07	2.12E+09	6.40E+09
CL	0.	0.	1.16E-05	9.47E-03	6.88E+00	4.05E+03	1.69E+06	4.28E+08	4.38E+10	1.04E+12	1.02E+12
CL+	5.35E-08	7.72E-02	1.03E+01	1.03E+03	1.74E+04	3.41E+06	4.92E+08	4.55E+10	1.82E+12	1.81E+13	8.71E+12
CL++	5.45E+01	2.72E+03	1.33E+05	5.90E+06	2.09E+08	3.99E+09	6.19E+10	2.24E+12	3.98E+13	2.09E+14	7.43E+13
CL+3	8.82E+06	1.47E+08	2.41E+09	3.73E+10	5.09E+11	5.36E+12	2.84E+13	6.33E+13	5.65E+14	1.99E+15	9.54E+14
CL+4	7.68E+11	4.26E+12	2.33E+13	1.23E+14	6.08E+14	2.60E+15	9.04E+15	1.47E+16	2.25E+16	6.66E+16	6.54E+16
CL+5	7.49E+13	2.35E+14	7.33E+14	2.27E+15	6.95E+15	2.13E+16	6.66E+16	2.24E+17	7.33E+17	2.32E+18	7.50E+18
H-	7.79E+07	1.40E+09	3.27E+10	9.96E+11	2.97E+13	8.38E+14	2.09E+16	4.22E+17	6.54E+18	8.41E+19	1.00E+21
H	1.01E+15	5.93E+15	4.46E+16	4.35E+17	4.17E+18	3.81E+19	3.14E+20	2.16E+21	1.15E+22	4.92E+22	1.78E+23
H+	2.08E+18	6.57E+18	2.08E+19	6.53E+19	2.04E+20	6.20E+20	1.77E+21	4.42E+21	9.25E+21	1.65E+22	2.92E+22
O-	0.	0.	0.	6.45E-05	4.06E-01	1.78E+03	4.43E+06	4.93E+09	1.79E+12	1.08E+14	1.06E+14
O	0.	3.19E-04	6.74E-02	1.68E+02	3.38E+05	4.83E+08	3.97E+11	1.50E+14	1.83E+16	3.76E+17	1.12E+17
O+	1.77E-01	1.07E+02	4.86E+04	1.49E+07	7.03E+08	3.34E+11	9.48E+13	1.31E+16	6.25E+17	5.36E+18	7.78E+17
O++	1.66E+04	3.45E+06	5.77E+08	7.85E+10	7.77E+12	3.66E+14	1.19E+16	6.41E+17	1.36E+19	6.18E+19	7.06E+18
O+3	4.80E+08	3.35E+10	1.90E+12	9.17E+13	3.60E+15	1.01E+17	1.49E+18	1.66E+19	1.77E+20	5.38E+20	7.78E+19
O+4	4.33E+12	1.01E+14	1.93E+15	3.22E+16	4.67E+17	5.50E+18	4.70E+19	2.55E+20	1.25E+21	3.21E+21	9.47E+20
O+5	9.31E+15	7.36E+16	4.63E+17	2.87E+18	1.59E+19	8.05E+19	3.56E+20	1.35E+21	4.20E+21	1.15E+22	1.12E+22
O+6	6.10E+17	2.63E+18	9.25E+18	2.94E+19	8.72E+19	2.43E+20	6.39E+20	1.68E+21	4.80E+21	1.77E+22	9.13E+22
O+7	4.18E+17	6.00E+17	7.05E+17	7.60E+17	8.01E+17	8.62E+17	1.01E+18	1.49E+18	3.53E+18	2.22E+19	9.75E+20
O+8	6.45E+15	3.07E+15	1.20E+15	4.43E+14	1.62E+14	7.14E+13	3.87E+13	3.46E+13	7.69E+13	1.04E+15	6.30E+17
N	0.	2.60E-03	5.93E-01	9.33E+02	9.43E+05	6.11E+08	2.41E+11	5.07E+13	4.15E+15	9.86E+16	1.37E+17
N+	1.12E+00	6.15E+02	2.25E+05	4.44E+07	1.41E+09	3.03E+11	4.13E+13	3.17E+15	1.01E+17	1.01E+18	6.83E+17
N++	7.38E+04	1.40E+07	1.87E+09	1.62E+11	8.22E+12	1.92E+14	3.75E+15	1.13E+17	1.60E+18	8.43E+18	4.49E+18
N+3	1.33E+09	8.46E+10	3.86E+12	1.19E+14	2.40E+15	3.21E+16	2.66E+17	2.05E+18	1.46E+19	5.15E+19	3.47E+19
N+4	4.78E+12	1.03E+14	1.62E+15	1.79E+16	1.40E+17	8.47E+17	4.20E+18	1.72E+19	6.40E+19	1.90E+20	2.62E+20
N+5	5.88E+14	6.28E+15	5.01E+16	2.87E+17	1.19E+18	3.96E+18	1.16E+19	3.22E+19	8.39E+19	2.66E+20	1.21E+21
N+6	9.69E+15	3.76E+16	1.06E+17	2.13E+17	3.18E+17	4.02E+17	5.07E+17	7.42E+17	1.42E+18	6.07E+18	1.46E+20
N+7	6.28E+15	8.17E+15	7.66E+15	5.22E+15	2.76E+15	1.35E+15	7.55E+14	6.22E+14	9.84E+14	7.17E+15	1.47E+18
TOTAL	1.20E+19	3.72E+19	1.16E+20	3.64E+20	1.14E+21	3.53E+21	1.08E+22	3.25E+22	9.68E+22	2.96E+23	9.65E+23

EQUILIBRIUM COMPOSITION FOR 0.99 WATER + 0.01 AIR + 7.2E-5 NACL (999,999°K)

CONCENTRATIONS IN PARTICLES/CM3

SPECIES	LOG10 OF DENSITY RATIO (STANDARD DENSITY = 1,0000E+00 GM/C**3)										
	-4.50	-4.00	-3.50	-3.00	-2.50	-2.00	-1.50	-1.00	-.50	0.00	.50
E-	1.04E+19	3.25E+19	9.96E+19	3.07E+20	9.16E+20	2.76E+21	8.26E+21	2.45E+22	7.07E+22	2.01E+23	6.04E+23
NA	0.	0.	0.	3.77E-05	2.66E-02	1.68E+01	9.11E+03	3.87E+06	9.42E+08	1.05E+11	3.77E+12
NA+	5.19E-05	7.85E-03	1.00E+00	6.83E+01	5.21E+02	1.11E+05	2.05E+07	3.05E+09	2.74E+11	1.21E+13	1.76E+14
NA++	8.93E+00	4.65E+02	2.24E+04	9.68E+05	3.44E+07	6.72E+08	1.55E+10	8.42E+11	2.98E+13	5.73E+14	4.20E+15
NA+3	2.76E+06	4.72E+07	7.71E+08	1.18E+10	1.63E+11	1.82E+12	1.03E+13	3.41E+13	5.06E+14	4.75E+15	2.14E+16
NA+4	4.15E+11	2.32E+12	1.27E+13	6.74E+13	3.39E+14	1.54E+15	5.62E+15	9.27E+15	2.39E+16	1.22E+17	4.15E+17
NA+5	7.52E+13	2.37E+14	7.44E+14	2.32E+15	7.22E+15	2.24E+16	7.00E+16	2.30E+17	7.37E+17	2.26E+18	7.12E+18
CL-	0.	0.	0.	0.	0.	8.76E-04	1.43E+00	1.80E+03	1.28E+06	4.10E+08	4.42E+10
CL	0.	0.	0.	1.42E-04	9.99E-02	6.32E+01	3.43E+04	1.46E+07	3.59E+09	4.06E+11	1.46E+13
CL+	1.75E-05	2.65E-03	3.41E-01	3.10E+01	5.12E+02	1.09E+05	2.02E+07	3.02E+09	2.73E+11	1.21E+13	1.78E+14
CL++	3.86E+00	2.01E+02	9.66E+03	4.15E+05	1.46E+07	2.68E+08	5.22E+09	2.84E+11	1.01E+13	1.94E+14	1.44E+15
CL+3	1.58E+06	2.71E+07	4.42E+08	6.76E+09	9.31E+10	1.03E+12	5.66E+12	1.48E+13	2.22E+14	2.10E+15	9.50E+15
CL+4	4.15E+11	2.32E+12	1.27E+13	6.72E+13	3.36E+14	1.51E+15	5.45E+15	7.79E+15	1.39E+16	7.16E+16	2.49E+17
CL+5	7.52E+13	2.37E+14	7.44E+14	2.37E+15	7.23E+15	2.24E+16	7.02E+16	2.31E+17	7.42E+17	2.32E+18	7.31E+18
H-	2.30E+07	4.21E+08	1.04E+10	3.01E+11	8.59E+12	2.38E+14	6.21E+15	1.42E+17	2.55E+18	3.49E+19	4.14E+20
H	5.51E+14	3.25E+15	2.61E+16	2.49E+17	2.35E+18	2.16E+19	1.88E+20	1.45E+21	9.04E+21	4.35E+22	1.72E+23
H+	2.08E+18	6.57E+18	2.08E+19	6.55E+19	2.06E+20	6.36E+20	1.89E+21	5.12E+21	1.18E+22	2.27E+22	3.58E+22
O-	0.	0.	0.	0.	1.46E-04	1.40E+00	7.61E+03	2.21E+07	2.72E+10	1.05E+13	1.08E+15
O	0.	0.	0.	4.80E-02	2.62E+02	8.34E+05	1.52E+09	1.49E+12	6.34E+14	8.59E+16	2.83E+18
O+	0.	4.33E-03	9.88E+00	1.06E+04	1.20E+06	1.29E+09	7.98E+11	2.74E+14	4.31E+16	2.29E+18	3.09E+19
O++	2.98E-01	3.73E+02	3.18E+05	1.62E+08	4.38E+10	3.95E+12	2.35E+14	2.94E+16	1.87E+18	4.24E+19	2.86E+20
O+3	2.60E+04	1.07E+07	3.13E+09	5.75E+11	6.29E+13	3.73E+15	9.07E+16	1.74E+18	4.54E+19	5.15E+20	2.14E+21
O+4	7.60E+08	1.03E+11	1.01E+13	6.47E+14	2.60E+16	6.33E+17	9.03E+18	6.74E+19	6.03E+20	3.72E+21	1.16E+22
O+5	4.85E+12	2.17E+14	7.27E+15	1.65E+17	2.49E+18	2.48E+19	1.71E+20	8.79E+20	3.57E+21	1.30E+22	3.87E+22
O+6	1.65E+15	2.97E+16	4.34E+17	4.59E+18	3.40E+19	1.77E+20	6.71E+20	2.09E+21	5.81E+21	1.46E+22	4.80E+22
O+7	1.11E+17	8.45E+17	5.04E+18	2.11E+19	6.05E+19	1.23E+20	1.90E+20	2.67E+20	4.13E+20	7.87E+20	3.60E+21
O+8	9.32E+17	2.43E+18	4.97E+18	7.22E+18	7.37E+18	5.53E+18	3.42E+18	2.21E+18	1.98E+18	3.18E+18	2.49E+19
N	0.	0.	1.57E-05	8.74E-02	3.51E+02	8.65E+05	1.19E+09	8.23E+11	2.31E+14	2.31E+16	7.55E+17
N+	0.	1.27E-02	1.39E+01	9.46E+03	1.11E+06	9.22E+08	4.32E+11	1.05E+14	1.09E+16	4.26E+17	5.69E+18
N++	1.48E+00	7.14E+02	2.93E+05	9.32E+07	1.89E+10	1.46E+12	8.76E+13	7.75E+15	3.16E+17	5.42E+18	3.63E+19
N+3	7.19E+04	1.14E+07	1.61E+09	1.85E+11	1.52E+13	7.34E+14	1.62E+16	3.00E+17	5.14E+18	4.30E+19	1.77E+20
N+4	8.00E+08	4.21E+10	2.02E+12	8.27E+13	2.58E+15	5.36E+16	6.92E+17	5.50E+18	3.78E+19	1.72E+20	5.35E+20
N+5	1.44E+12	2.60E+13	4.50E+14	7.06E+15	9.06E+16	8.43E+17	5.46E+18	2.53E+19	8.43E+19	2.33E+20	6.70E+20
N+6	3.39E+14	2.51E+15	1.87E+16	1.29E+17	7.35E+17	3.04E+18	8.87E+18	1.98E+19	3.65E+19	6.78E+19	2.22E+20
N+7	1.62E+16	4.98E+16	1.47E+17	3.87E+17	8.28E+17	1.30E+18	1.53E+18	1.53E+18	1.56E+18	2.19E+18	9.97E+18
TOTAL	1.36E+19	4.24E+19	1.31E+20	4.02E+20	1.23E+21	3.75E+21	1.14E+22	3.44E+22	1.02E+23	3.00E+23	9.18E+23

EQUILIBRIUM COMPOSITION FOR 0.99 WATER + 0.01 AIR + 7.2E-5 NACL (1,584,893°K)

CONCENTRATIONS IN PARTICLES/CM3

SPECIES	LOG10 OF DENSITY RATIO (STANDARD DENSITY = 1.0000E+00 GM/CM3)										
	-4.50	-4.00	-3.50	-3.00	-2.50	-2.00	-1.50	-1.00	-.50	0.00	.50
E-	1.05E+19	3.33E+19	1.05E+20	3.31E+20	1.03E+21	3.19E+21	9.67E+21	2.86E+22	8.27E+22	2.32E+23	6.53E+23
NA	0.	0.	0.	0.	2.36E-04	1.84E-01	1.20E+02	6.42E+04	2.37E+07	5.23E+09	6.57E+11
NA+	0.	1.17E-04	1.68E-02	1.60E+00	9.74E+00	2.48E+03	5.44E+05	1.00E+08	1.33E+10	1.11E+12	5.50E+13
NA++	5.51E-01	1.92E+01	1.00E+03	4.76E+04	1.82E+06	2.95E+07	8.93E+08	5.80E+10	2.86E+12	9.61E+13	1.99E+15
NA+3	3.51E+05	6.18E+06	1.06E+08	1.73E+09	2.55E+10	2.90E+11	1.30E+12	5.13E+12	9.75E+13	1.40E+15	1.39E+16
NA+4	2.08E+11	1.17E+12	6.54E+12	3.54E+13	1.82E+14	8.36E+14	2.98E+15	2.50E+15	9.91E+15	6.43E+16	3.39E+17
NA+5	7.54E+13	2.38E+14	7.50E+14	2.36E+15	7.38E+15	2.31E+16	7.27E+16	2.37E+17	7.46E+17	2.33E+18	7.21E+18
CL-	0.	0.	0.	0.	0.	1.52E-05	3.02E-02	4.76E+01	5.08E+04	1.15E+07	1.09E+10
CL	0.	0.	0.	0.	2.47E-03	1.93E+00	1.26E+03	6.73E+05	2.49E+08	5.51E+10	6.75E+12
CL+	0.	8.49E-05	1.21E-02	1.21E+00	2.42E+01	6.15E+03	1.35E+06	2.49E+08	3.30E+10	2.77E+12	1.35E+14
CL++	2.67E-01	1.48E+01	7.61E+02	3.62E+04	1.38E+06	2.20E+07	6.44E+08	4.19E+10	2.07E+12	6.97E+13	1.45E+15
CL+3	2.79E+05	4.91E+06	8.43E+07	1.38E+09	2.02E+10	2.34E+11	1.03E+12	3.91E+12	7.44E+13	1.07E+15	1.07E+16
CL+4	2.08E+11	1.17E+12	6.54E+12	3.54E+13	1.82E+14	8.33E+14	2.95E+15	2.23E+15	7.89E+15	5.13E+16	2.72E+17
CL+5	7.54E+13	2.38E+14	7.50E+14	2.36E+15	7.38E+15	2.31E+16	7.27E+16	2.37E+17	7.48E+17	2.30E+18	7.28E+18
H-	5.54E+06	1.04E+08	2.74E+09	8.56E+10	2.62E+12	7.74E+13	2.13E+15	5.22E+16	1.05E+18	1.61E+19	1.46E+20
H	2.77E+14	1.64E+15	1.38E+16	1.36E+17	1.34E+18	1.28E+19	1.16E+20	9.62E+20	6.72E+21	3.67E+22	1.58E+23
H+	2.08E+18	6.58E+18	2.08E+19	6.56E+19	2.07E+20	6.45E+20	1.96E+21	5.62E+21	1.41E+22	2.91E+22	4.93E+22
O-	0.	0.	0.	0.	0.	1.02E-04	2.64E+00	3.11E+04	1.49E+08	2.21E+11	1.09E+14
O	0.	0.	0.	0.	7.68E-03	1.18E+02	1.01E+06	4.03E+09	6.68E+12	3.54E+15	6.20E+17
O+	0.	0.	6.19E-05	1.74E-01	7.09E+01	3.56E+05	1.02E+09	1.41E+12	8.35E+14	1.68E+17	1.15E+19
O++	0.	3.22E-03	5.04E+00	6.77E+03	6.43E+06	1.87E+09	6.08E+11	2.96E+14	6.53E+16	5.27E+18	1.57E+20
O+3	4.81E-01	2.61E+02	1.35E+05	6.32E+07	2.38E+10	5.70E+12	4.57E+14	3.58E+16	3.05E+18	1.05E+20	1.50E+21
O+4	4.27E+04	7.45E+06	1.25E+09	1.95E+11	2.59E+13	2.48E+15	1.33E+17	2.58E+18	7.70E+19	1.20E+21	9.14E+21
O+5	1.33E+09	7.44E+10	4.06E+12	2.10E+14	9.59E+15	3.42E+17	7.97E+18	1.05E+20	8.71E+20	6.51E+21	2.90E+22
O+6	8.23E+12	1.50E+14	2.73E+15	4.86E+16	8.11E+17	1.15E+19	1.22E+20	8.75E+20	4.32E+21	1.55E+22	4.48E+22
O+7	8.75E+15	5.56E+16	3.68E+17	2.52E+18	1.71E+19	1.04E+20	4.95E+20	1.70E+21	4.39E+21	8.78E+21	1.83E+22
O+8	1.04E+18	3.25E+18	1.01E+19	3.05E+19	8.65E+19	2.14E+20	4.19E+20	6.27E+20	7.82E+20	9.23E+20	1.53E+21
N	0.	0.	0.	0.	2.90E-02	1.79E+02	7.47E+05	1.80E+09	2.04E+12	7.99E+14	1.15E+17
N+	0.	0.	9.01E-04	8.58E-01	1.80E+02	3.63E+05	5.08E+08	4.22E+11	1.72E+14	2.55E+16	1.44E+18
N++	1.68E-04	9.02E-02	4.58E+01	2.06E+04	7.08E+06	9.53E+08	2.01E+11	5.91E+13	8.95E+15	5.34E+17	1.30E+19
N+3	2.17E+01	3.79E+03	6.37E+05	1.00E+08	1.36E+10	1.37E+12	6.93E+13	4.47E+15	2.61E+17	6.65E+18	7.79E+19
N+4	1.65E+06	9.22E+07	5.03E+09	2.61E+11	1.23E+13	4.76E+14	1.28E+16	1.64E+17	3.42E+18	3.92E+19	2.45E+20
N+5	2.66E+10	4.79E+11	8.57E+12	1.51E+14	2.53E+15	3.84E+16	4.87E+17	4.64E+18	3.31E+19	1.83E+20	6.68E+20
N+6	9.54E+13	5.67E+14	3.44E+15	2.14E+16	1.35E+17	8.31E+17	4.70E+18	2.23E+19	8.17E+19	2.23E+20	5.28E+20
N+7	1.65E+16	5.18E+16	1.62E+17	5.02E+17	1.52E+16	4.37E+18	1.14E+19	2.53E+19	4.72E+19	7.18E+19	1.22E+20
TOTAL	1.37E+19	4.32E+19	1.37E+20	4.30E+20	1.35E+21	4.19E+21	1.28E+22	3.85E+22	1.14E+23	3.31E+23	9.67E+23

EQUILIBRIUM COMPOSITION FOR 0.99 WATER + 0.01 AIR + 7.2E-5 NACL (2,511,886°K)

CONCENTRATIONS IN PARTICLES/CM3

SPECIES LOG10 OF DENSITY RATIO (STANDARD DENSITY = 1.0000E+00 GM/CM3)

SPECIES	-4.50	-4.00	-3.50	-3.00	-2.50	-2.00	-1.50	-1.00	-.50	0.00	.50
E-	1.05E+19	3.33E+19	1.05E+20	3.33E+20	1.05E+21	3.30E+21	1.03E+22	3.17E+22	9.50E+22	2.73E+23	7.70E+23
NA	0.	0.	0.	0.	0.	2.17E-03	1.82E+00	1.34E+03	7.38E+05	2.70E+08	6.26E+10
NA+	0.	0.	3.95E-04	3.91E-02	2.17E-01	6.29E+01	1.70E+04	4.12E+06	7.75E+08	1.02E+11	8.90E+12
NA++	2.06E-02	1.13E+00	5.96E+01	2.89E+03	1.14E+05	1.75E+06	6.08E+07	4.99E+09	3.21E+11	1.58E+13	5.48E+14
NA+3	5.62E+04	9.93E+05	1.72E+07	2.85E+08	4.32E+09	5.22E+10	2.01E+11	9.17E+11	2.14E+13	4.05E+14	5.95E+15
NA+4	1.04E+11	5.86E+11	5.27E+12	1.78E+13	9.28E+13	4.34E+14	1.55E+15	5.25E+14	4.45E+15	3.37E+16	2.21E+17
NA+5	7.55E+13	2.39E+14	7.53E+14	2.37E+15	7.47E+15	2.35E+16	7.41E+16	2.39E+17	7.52E+17	2.36E+18	7.34E+18
CL-	0.	0.	0.	0.	0.	0.	4.68E-04	1.06E+00	1.79E+03	1.84E+06	1.28E+09
CL	0.	0.	0.	0.	4.88E-05	4.43E-02	3.71E+01	2.72E+04	1.50E+07	5.51E+09	1.28E+12
CL+	0.	0.	4.78E-04	4.90E-02	9.84E-01	2.85E+02	7.72E+04	1.06E+07	3.51E+09	4.63E+11	4.03E+13
CL++	2.26E-02	1.24E+00	6.55E+01	3.19E+03	1.26E+05	1.99E+06	7.25E+07	5.84E+09	3.83E+11	1.88E+13	6.54E+14
CL+3	5.52E+04	9.76E+05	1.69E+07	2.80E+08	4.25E+09	5.14E+10	2.01E+11	1.01E+12	2.35E+13	4.46E+14	6.55E+15
CL+4	1.00E+11	5.86E+11	3.27E+12	1.78E+13	9.27E+13	4.34E+14	1.55E+15	5.15E+14	4.37E+15	3.31E+16	2.17E+17
CL+5	7.55E+13	2.39E+14	7.53E+14	2.37E+15	7.47E+15	2.35E+16	7.41E+16	2.39E+17	7.52E+17	2.36E+18	7.34E+18
H-	1.34E+06	2.52E+07	6.67E+08	2.10E+10	6.58E+11	2.03E+13	6.10E+14	1.69E+16	4.02E+17	7.30E+18	9.96E+19
H	1.38E+14	8.21E+14	6.89E+15	6.87E+16	6.82E+17	6.70E+18	6.43E+19	5.81E+20	4.60E+21	2.90E+22	1.41E+23
H+	2.08E+18	6.58E+18	2.08E+19	6.57E+19	2.07E+20	6.51E+20	2.02E+21	6.00E+21	1.67E+22	3.67E+22	6.71E+22
O-	0.	0.	0.	0.	0.	0.	1.33E-04	5.50E+00	1.16E+05	8.55E+08	1.91E+12
O	0.	0.	0.	0.	0.	5.11E-03	1.03E+02	1.38E+06	9.79E+09	2.50E+13	1.98E+16
O+	0.	0.	0.	0.	4.05E-03	3.22E+01	2.09E+05	9.27E+08	2.24E+12	2.05E+15	6.13E+17
O++	0.	0.	5.61E-04	8.26E-01	9.51E+02	3.68E+05	2.58E+08	3.83E+11	3.21E+14	1.10E+17	1.31E+19
O+3	1.27E-04	7.04E-02	3.78E+01	1.92E+04	8.67E+06	3.08E+09	4.01E+11	9.35E+13	2.79E+16	3.68E+18	1.85E+20
O+4	2.99E+01	5.29E+03	9.19E+05	1.54E+08	2.40E+10	3.22E+12	3.14E+14	1.23E+16	1.34E+18	7.07E+19	1.59E+21
O+5	7.16E+06	4.05E+08	2.24E+10	1.21E+12	6.18E+13	2.84E+15	1.04E+17	2.30E+18	2.87E+19	6.27E+20	6.69E+21
O+6	3.14E+11	5.65E+12	1.01E+14	1.80E+15	3.12E+16	5.14E+17	7.61E+18	9.22E+19	8.10E+20	6.75E+21	3.61E+22
O+7	3.76E+15	2.18E+16	1.28E+17	7.60E+17	4.57E+18	2.76E+19	1.63E+20	8.88E+20	4.15E+21	1.51E+22	4.31E+22
O+8	1.04E+18	3.28E+18	1.03E+19	3.23E+19	9.98E+19	3.02E+20	8.70E+20	2.32E+21	5.45E+21	1.00E+22	1.67E+22
N	0.	0.	0.	0.	0.	4.99E-02	3.52E+02	1.83E+06	5.74E+09	7.54E+12	3.86E+15
N+	0.	0.	0.	5.57E-04	7.89E-02	2.09E+02	4.75E+05	8.12E+08	8.71E+11	4.11E+14	7.93E+16
N++	0.	8.00E-05	4.17E-02	1.98E+01	7.56E+03	1.15E+06	3.83E+08	2.15E+11	8.16E+13	1.43E+16	1.10E+18
N+3	4.61E-02	8.12E+00	1.40E+03	2.30E+05	3.44E+07	4.17E+09	2.68E+11	3.28E+13	4.31E+15	2.92E+17	9.50E+18
N+4	2.40E+04	1.35E+06	7.43E+07	3.97E+09	1.98E+11	8.68E+12	2.73E+14	2.12E+15	1.02E+17	2.78E+18	4.04E+19
N+5	2.25E+09	4.03E+10	7.18E+11	1.26E+13	2.14E+14	3.40E+15	4.75E+16	5.09E+17	4.90E+18	5.50E+19	3.79E+20
N+6	4.55E+13	2.63E+14	1.53E+15	8.96E+15	5.29E+16	3.13E+17	1.82E+18	1.01E+19	5.04E+19	2.30E+20	7.94E+20
N+7	1.65E+16	5.21E+16	1.64E+17	5.15E+17	1.60E+18	4.92E+18	1.47E+19	4.18E+19	1.10E+20	2.36E+20	4.33E+20
TOTAL	1.37E+19	4.33E+19	1.37E+20	4.32E+20	1.36E+21	4.29E+21	1.34E+22	4.16E+22	1.26E+23	3.73E+23	1.08E+24

EQUILIBRIUM COMPOSITION FOR 0.99 WATER + 0.01 AIR + 7.2E-5 NACL (3,981,071°K)

CONCENTRATIONS IN PARTICLES/CM3

SPECIES LOG10 OF DENSITY RATIO (STANDARD DENSITY = 1.0000E+00 GM/CM3)

SPECIES	-4.50	-4.00	-3.50	-3.00	-2.50	-2.00	-1.50	-1.00	-.50	0.00	.50
E-	1.06E+19	3.34E+19	1.05E+20	3.33E+20	1.05E+21	3.32E+21	1.04E+22	3.26E+22	1.00E+23	2.99E+23	8.60E+23
NA	0.	0.	0.	0.	0.	3.35E-05	3.08E-02	2.65E+01	1.94E+04	1.08E+07	4.09E+09
NA+	0.	0.	1.33E-05	1.33E-05	6.61E-03	2.07E+00	6.06E+02	1.68E+05	4.04E+07	7.67E+09	1.05E+12
NA++	1.59E-03	8.72E-02	4.52E+00	2.26E+02	9.06E+03	1.39E+05	4.69E+06	4.22E+08	3.38E+10	2.23E+12	1.13E+14
NA+3	1.06E+04	1.87E+05	3.25E+06	5.42E+07	8.31E+08	1.02E+10	3.81E+10	1.70E+11	4.59E+12	1.08E+14	2.09E+15
NA+4	5.19E+10	2.93E+11	1.64E+12	8.94E+12	4.67E+13	2.20E+14	7.90E+14	2.18E+14	2.00E+15	1.71E+16	1.31E+17
NA+5	7.50E+13	2.39E+14	7.55E+14	2.38E+15	7.52E+15	2.37E+16	7.48E+16	2.39E+17	7.54E+17	2.37E+18	7.43E+18
CL-	0.	0.	0.	0.	0.	0.	0.	1.64E-02	3.70E+01	6.11E+04	6.67E+07
CL	0.	0.	0.	0.	0.	1.05E-03	9.61E-01	8.26E+02	6.06E+05	3.35E+08	1.27E+11
CL+	0.	0.	2.22E-05	2.30E-03	4.58E-02	1.39E+01	4.04E+03	1.12E+06	2.70E+08	5.11E+10	6.96E+12
CL++	2.21E-03	1.22E-01	6.45E+00	3.17E+02	1.28E+04	2.01E+05	7.72E+06	6.94E+08	5.56E+10	3.07E+12	1.66E+14
CL+3	1.19E+04	2.11E+05	3.66E+06	6.11E+07	9.38E+08	1.16E+10	4.44E+10	2.37E+11	6.39E+12	1.50E+14	2.90E+15
CL+4	5.19E+10	2.93E+11	1.64E+12	8.94E+12	4.67E+13	2.21E+14	7.93E+14	2.46E+14	2.26E+15	1.92E+16	1.47E+17
CL+5	7.56E+13	2.39E+14	7.55E+14	2.38E+15	7.52E+15	2.37E+16	7.48E+16	2.39E+17	7.54E+17	2.37E+18	7.41E+18
H-	3.29E+05	6.18E+06	1.68E+08	5.17E+09	1.63E+11	5.10E+12	1.57E+14	4.66E+15	1.25E+17	2.75E+18	4.49E+19
H	6.92E+13	4.11E+14	3.45E+15	3.44E+16	3.43E+17	3.40E+18	3.34E+19	3.17E+20	2.77E+21	2.08E+22	1.16E+23
H+	2.08E+18	6.58E+18	2.08E+19	6.57E+19	2.08E+20	6.54E+20	2.05E+21	6.26E+21	1.80E+22	4.54E+22	9.23E+22
O-	0.	0.	0.	0.	0.	0.	0.	9.06E-08	4.19E+01	9.74E+05	8.22E+09
O	0.	0.	0.	0.	0.	0.	2.19E-02	4.65E+02	6.99E+06	5.45E+10	1.60E+14
O+	0.	0.	0.	0.	0.	1.19E-02	9.21E+01	4.29E+05	3.11E+09	8.29E+12	8.74E+15
O++	0.	0.	0.	5.79E-04	7.03E-01	2.90E+02	2.40E+05	5.52E+08	8.74E+11	8.13E+14	3.18E+17
O+3	0.	1.09E-04	5.96E-02	3.11E+01	1.47E+04	5.58E+06	8.34E+08	2.72E+11	1.50E+14	4.96E+16	7.43E+18
O+4	1.10E-01	1.96E+01	3.45E+03	5.89E+05	9.57E+07	1.39E+10	1.57E+12	7.66E+13	1.44E+16	1.73E+18	1.02E+20
O+5	1.56E+05	8.80E+06	4.92E+08	2.69E+10	1.42E+12	6.86E+13	2.78E+15	6.80E+16	6.21E+17	2.75E+19	6.64E+20
O+6	5.92E+10	7.03E+11	1.24E+13	2.22E+14	3.85E+15	6.36E+16	9.61E+17	1.20E+19	9.45E+19	1.26E+21	1.24E+22
O+7	1.85E+15	1.04E+16	6.19E+16	3.56E+17	2.08E+18	1.22E+19	7.10E+19	4.05E+20	2.18E+21	1.13E+22	5.00E+22
O+8	1.04E+18	3.29E+18	1.04E+19	3.27E+19	1.02E+20	3.18E+20	9.72E+20	2.89E+21	8.16E+21	2.05E+22	4.09E+22
N	0.	0.	0.	0.	0.	4.06E-05	3.43E-01	2.49E+03	1.38E+07	8.19E+10	5.79E+13
N+	0.	0.	0.	0.	1.21E-04	3.51E-01	9.47E+02	2.22E+06	4.03E+09	4.28E+12	2.08E+15
N++	0.	0.	1.39E-04	6.76E-02	2.68E+01	4.21E+03	1.59E+06	1.21E+09	7.29E+11	2.65E+14	4.87E+16
N+3	3.42E-04	6.05E-02	1.05E+01	1.76E+03	2.71E+05	3.49E+07	2.36E+09	3.68E+11	7.47E+13	9.65E+15	6.80E+17
N+4	8.41E+02	4.73E+04	2.63E+06	1.42E+08	7.26E+09	3.31E+11	1.11E+13	5.01E+13	3.46E+15	1.62E+17	4.51E+18
N+5	3.80E+08	6.88E+09	1.22E+11	2.15E+12	3.65E+13	5.84E+14	8.18E+15	8.17E+16	6.56E+17	1.13E+19	1.29E+20
N+6	2.25E+13	1.29E+14	7.47E+14	4.34E+15	2.53E+16	1.40E+17	8.64E+17	4.95E+18	2.71E+19	1.67E+20	8.01E+20
N+7	1.65E+16	5.23E+16	1.65E+17	5.20E+17	1.63E+18	5.09E+18	1.57E+19	4.74E+19	1.38E+20	3.45E+30	7.22E+20
TOTAL	1.37E+19	4.33E+19	1.37E+20	4.33E+20	1.37E+21	4.31E+21	1.36E+22	4.26E+22	1.32E+23	3.99E+23	1.17E+24

EQUILIBRIUM COMPOSITION FOR 0.99 WATER + 0.01 AIR + 7.2E-5 NACL (6,309,573^{0}K)

CONCENTRATIONS IN PARTICLES/CM3

SPECIES	LOG10 OF DENSITY RATIO (STANDARD DENSITY = 1.0000E+00 GM/CM3)										
	-4.50	-4.00	-3.50	-3.00	-2.50	-2.00	-1.50	-1.00	-.50	0.00	.50
E-	1.06E+19	3.34E+19	1.05E+20	3.33E+20	1.05E+21	3.33E+21	1.05E+22	3.30E+22	1.03E+23	3.13E+23	9.21E+23
NA	0.	0.	0.	0.	0.	0.	6.34E-04	5.68E-01	4.99E+02	3.57E+05	1.90E+08
NA+	0.	0.	0.	5.65E-05	2.74E-04	8.48E-02	2.58E+01	7.64E+03	2.09E+06	4.96E+08	9.16E+10
NA++	1.46E-04	8.05E-03	4.27E-01	2.10E+01	8.45E+02	1.24E+04	4.23E+05	4.01E+07	3.57E+09	2.83E+11	1.84E+13
NA+3	2.21E+03	3.92E+04	6.81E+05	1.14E+07	1.76E+08	2.18E+09	7.98E+09	3.43E+10	9.98E+11	2.67E+13	6.22E+14
NA+4	2.69E+10	1.46E+11	8.18E+11	4.47E+12	2.34E+13	1.11E+14	3.99E+14	9.59E+13	9.17E+14	8.38E+15	7.11E+16
NA+5	7.56E+13	2.39E+14	7.56E+14	2.39E+15	7.54E+15	2.38E+16	7.52E+16	2.39E+17	7.55E+17	2.38E+18	7.49E+18
CL-	0.	0.	0.	0.	0.	0.	0.	2.41E-04	6.37E-01	1.39E+03	2.17E+06
CL	0.	0.	0.	0.	0.	2.71E-05	2.60E-02	2.40E+01	2.04E+04	1.46E+07	7.77E+09
CL+	0.	0.	0.	1.20E-04	2.33E-03	7.23E-01	2.20E+02	6.51E+04	1.79E+07	4.22E+09	7.79E+11
CL++	2.37E-04	1.31E-02	6.94E-01	3.42E+01	1.39E+03	2.18E+04	8.55E+05	8.10E+07	7.21E+09	5.71E+11	3.71E+13
CL+3	2.72E+03	4.81E+04	8.37E+05	1.40E+07	2.16E+08	2.70E+09	1.02E+10	5.56E+10	1.62E+12	4.33E+13	1.01E+15
CL+4	2.60E+10	1.46E+11	8.18E+11	4.47E+12	2.34E+13	1.11E+14	4.01E+14	1.18E+14	1.13E+15	1.03E+16	8.72E+16
CL+5	7.56E+13	2.39E+14	7.56E+14	2.39E+15	7.54E+15	2.38E+16	7.52E+16	2.39E+17	7.55E+17	2.38E+18	7.48E+18
H-	8.16E+04	1.53E+06	4.06E+07	1.28E+09	4.05E+10	1.27E+12	3.97E+13	1.22E+15	3.53E+16	8.93E+17	1.75E+19
H	3.47E+13	2.06E+14	1.73E+15	1.72E+16	1.72E+17	1.71E+18	1.70E+19	1.65E+20	1.54E+21	1.28E+22	8.54E+22
H+	2.08E+18	6.58E+18	2.08E+19	6.58E+19	2.08E+20	6.56E+20	2.06E+21	6.41E+21	1.93E+22	5.30E+22	1.23E+23
O-	0.	0.	0.	0.	0.	0.	0.	0.	2.10E-02	9.25E+02	1.90E+07
O	0.	0.	0.	0.	0.	0.	1.26E-05	3.26E-01	7.03E+03	1.02E+08	7.10E+11
O+	0.	0.	0.	0.	0.	1.20E-05	1.08E-01	8.96E+02	6.23E+06	2.99E+10	7.21E+13
O++	0.	0.	0.	0.	1.58E-03	6.67E-01	5.86E+02	1.55E+06	3.51E+09	5.63E+12	4.79E+15
O+3	0.	0.	2.83E-04	1.49E-01	7.23E+01	2.85E+04	4.44E+06	1.65E+09	1.22E+12	6.59E+14	2.01E+17
O+4	1.18E-03	2.07E-01	3.65E+01	6.31E+03	1.04E+06	1.57E+08	1.88E+10	9.80E+11	2.38E+14	4.40E+16	4.88E+18
O+5	6.77E+03	3.83E+05	2.15E+07	1.18E+09	6.31E+10	3.14E+12	1.33E+14	3.43E+15	2.10E+16	1.34E+18	5.51E+19
O+6	7.58E+09	1.36E+11	2.43E+12	4.30E+13	7.45E+14	1.24E+16	1.89E+17	2.35E+18	1.39E+19	2.12E+20	3.28E+21
O+7	9.20E+14	5.27E+15	3.03E+16	1.75E+17	1.02E+18	5.93E+18	3.46E+19	2.01E+20	1.14E+21	6.91E+21	4.11E+22
O+8	1.04E+18	3.30E+18	1.04E+19	3.29E+19	1.03E+20	3.24E+20	1.01E+21	3.10E+21	9.29E+21	2.59E+22	6.00E+22
N	0.	0.	0.	0.	0.	0.	6.81E-04	5.80E+00	4.26E+04	2.14E+08	5.95E+11
N+	0.	0.	0.	0.	0.	1.31E-03	3.93E+00	1.08E+04	2.47E+07	4.15E+10	3.95E+13
N++	0.	0.	0.	5.21E-04	2.18E-01	3.33E+01	1.32E+04	1.15E+07	8.86E+09	4.99E+12	1.67E+15
N+3	0.	9.90E-04	1.73E-01	2.91E+01	4.57E+03	6.03E+05	4.15E+07	7.21E+09	1.81E+12	3.45E+14	4.14E+16
N+4	4.80E+01	2.70E+03	1.50E+05	8.18E+06	4.24E+08	1.97E+10	6.83E+11	2.03E+12	1.68E+14	1.09E+16	4.78E+17
N+5	6.20E+07	1.47E+09	2.01E+10	4.58E+11	7.82E+12	1.26E+14	1.77E+15	1.69E+16	1.02E+17	2.29E+18	3.71E+19
N+6	1.12E+13	6.44E+13	3.71E+14	2.15E+15	1.25E+16	7.29E+16	4.27E+17	2.49E+18	1.42E+19	1.05E+20	6.44E+20
N+7	1.66E+16	5.23E+16	1.65E+17	5.22E+17	1.64E+18	5.17E+18	1.61E+19	4.99E+19	1.51E+20	4.16E+20	9.75E+20
TOTAL	1.37E+19	4.33E+19	1.37E+20	4.33E+20	1.37E+21	4.32E+21	1.36E+22	4.29E+22	1.34E+23	4.13E+23	1.28E+24

EQUILIBRIUM COMPOSITION FOR 0.99 WATER + 0.01 AIR + 7.2E-5 NACL (9,999,999OK)

CONCENTRATIONS IN PARTICLES/CM3

SPECIES LOG10 OF DENSITY RATIO (STANDARD DENSITY = 1.0000E+00 GM/CM3)

SPECIES	-4.50	-4.00	-3.50	-3.00	-2.50	-2.00	-1.50	-1.00	-.50	0.00	.50
E-	1.06E+19	3.34E+19	1.06E+20	3.34E+20	1.05E+21	3.33E+21	1.05E+22	3.32E+22	1.04E+23	3.22E+23	9.68E+23
NA	0.	0.	0.	0.	0.	0.	1.51E-05	1.45E-02	1.33E+01	1.11E+04	7.49E+06
NA+	0.	0.	0.	0.	1.29E-05	4.05E-03	1.26E+00	3.84E+02	1.13E+05	3.05E+07	6.91E+09
NA++	1.51E-05	8.32E-04	4.42E-02	2.18E+00	6.78E+01	1.27E+03	4.27E+04	4.15E+06	3.91E+08	3.44E+10	2.65E+12
NA+3	4.95E+02	8.76E+03	1.52E+05	2.55E+06	3.94E+07	4.92E+08	1.78E+09	7.40E+09	2.24E+11	6.48E+12	1.70E+14
NA+4	1.30E+10	7.32E+10	4.09E+11	2.24E+12	1.17E+13	5.56E+13	2.00E+14	4.39E+13	4.29E+14	4.09E+15	3.70E+16
NA+5	7.56E+13	2.39E+14	7.56E+14	2.39E+15	7.55E+15	2.39E+16	7.54E+16	2.39E+17	7.56E+17	2.39E+18	7.53E+18
CL-	0.	0.	0.	0.	0.	0.	0.	0.	1.02E-02	2.63E+01	5.34E+04
CL	0.	0.	0.	0.	0.	0.	7.33E-04	7.05E-01	6.48E+02	5.39E+05	3.63E+08
CL+	0.	0.	0.	0.	1.29E-04	4.03E-02	1.25E+01	3.83E+03	1.12E+06	3.03E+08	6.87E+10
CL++	2.70E-05	1.49E-03	7.90E-02	3.90E+00	1.59E+02	2.49E+03	9.83E+04	9.56E+06	9.01E+08	7.93E+10	6.09E+12
CL+3	6.43E+02	1.14E+04	1.98E+05	3.37E+06	5.13E+07	6.42E+08	2.43E+09	1.32E+10	4.00E+11	1.15E+13	3.03E+14
CL+4	1.30E+10	7.37E+10	4.09E+11	2.20E+12	1.17E+13	5.57E+13	2.01E+14	5.70E+13	5.57E+14	5.30E+15	4.80E+16
CL+5	7.56E+13	2.39E+14	7.56E+14	2.39E+15	7.55E+15	2.39E+16	7.54E+16	2.39E+17	7.56E+17	2.39E+18	7.52E+18
H-	2.03E+04	3.81E+05	1.01E+07	3.19E+08	1.01E+10	3.18E+11	1.00E+13	3.11E+14	9.39E+15	2.62E+17	6.07E+18
H	1.74E+13	1.03E+14	8.64E+14	8.64E+15	8.63E+16	8.62E+17	8.57E+18	8.46E+19	8.14E+20	7.33E+21	5.66E+22
H+	2.08E+18	6.58E+18	2.08E+19	6.58E+19	2.08E+20	6.57E+20	2.07E+21	6.49E+21	2.00E+22	5.84E+22	1.51E+23
O-	0.	0.	0.	0.	0.	0.	0.	0.	1.58E-05	1.01E+00	3.79E+04
O	0.	0.	0.	0.	0.	0.	0.	4.09E-04	1.06E+01	2.20E+05	2.74E+09
O+	0.	0.	0.	0.	0.	0.	2.50E-04	2.27E+00	1.89E+04	1.27E+08	5.31E+11
O++	0.	0.	0.	0.	0.	3.09E-03	2.77E+00	8.03E+03	2.14E+07	4.68E+10	6.65E+13
O+3	0.	0.	0.	1.43E-03	7.01E-01	2.87E+02	4.45E+04	1.75E+07	1.50E+10	1.08E+13	5.22E+15
O+4	2.37E-05	4.23E-03	7.47E-01	1.30E+02	2.16E+04	3.30E+06	4.06E+08	2.16E+10	5.97E+12	1.41E+15	2.37E+17
O+5	4.40E+02	2.49E+04	1.40E+06	7.72E+07	4.14E+09	2.09E+11	9.06E+12	2.41E+14	1.08E+15	8.49E+16	4.95E+18
O+6	1.69E+09	3.03E+10	5.41E+11	9.58E+12	1.66E+14	2.78E+15	4.27E+16	5.31E+17	2.53E+18	3.88E+19	7.93E+20
O+7	4.60E+14	2.63E+15	1.51E+16	8.70E+16	5.04E+17	2.94E+18	1.72E+19	1.01E+20	5.84E+20	3.90E+21	2.83E+22
O+8	1.04E+18	3.30E+18	1.04E+19	3.29E+19	1.04E+20	3.27E+20	1.03E+21	3.20E+21	9.86E+21	2.91E+22	7.53E+22
N	0.	0.	0.	0.	0.	0.	0.	2.03E-02	1.73E+02	1.19E+06	5.34E+09
N+	0.	0.	0.	0.	0.	0.	2.50E-02	7.33E+01	2.00E+05	4.48E+08	6.73E+11
N++	0.	0.	0.	0.	2.73E-03	4.35E-01	1.76E+02	1.64E+05	1.44E+08	1.05E+11	5.35E+13
N+3	0.	2.67E-05	4.66E-03	7.86E-01	1.24E+02	1.66E+04	1.15E+06	2.10E+08	5.91E+10	1.42E+13	2.46E+15
N+4	3.68E+00	2.07E+02	1.16E+04	6.39E+05	3.28E+07	1.54E+09	5.44E+10	1.22E+11	1.11E+13	8.73E+14	5.24E+16
N+5	1.90E+07	3.40E+08	6.04E+09	1.06E+11	1.81E+12	2.93E+13	4.15E+14	3.87E+15	1.83E+16	4.79E+17	1.00E+19
N+6	5.61E+12	3.22E+13	1.85E+14	1.07E+15	6.20E+15	3.62E+16	2.12E+17	1.25E+18	7.30E+18	6.00E+19	4.43E+20
N+7	1.66E+16	5.24E+16	1.65E+17	5.23E+17	1.65E+18	5.20E+18	1.64E+19	5.11E+19	1.58E+20	4.63E+20	1.20E+21
TOTAL	1.37E+19	4.33E+19	1.37E+20	4.33E+20	1.37E+21	4.33E+21	1.37E+22	4.31E+22	1.36E+23	4.22E+23	1.28E+24

PRESSURE (BARS) OF 0.99 WATER + 0.01 AIR + 7.2E-5 NACL

LOG10 OF DENSITY RATIO (STANDARD DENSITY = 1.0000E+00 GM/CM3)

TEMP. (DEG K)	-4.50	-4.00	-3.50	-3.00	-2.50	-2.00	-1.50	-1.00	-.50	0.00
1000	1.450E-01	4.586E-01	1.450E+00	4.580E+00	1.444E+01	4.520E+01	1.384E+02	3.923E+02	7.867E+02	
2000	2.715E-01	9.202E-01	2.907E+00	9.185E+00	2.904E+01	9.185E+01	2.909E+02	9.248E+02	2.975E+03	9.913E+03
3000	5.357E-01	1.577E+00	4.757E+00	1.459E+01	4.528E+01	1.417E+02	4.482E+02	1.448E+03	4.950E+03	1.949E+04
4000	1.310E+00	3.472E+00	9.251E+00	2.542E+01	7.253E+01	2.141E+02	6.521E+02	2.066E+03	7.071E+03	2.867E+04
5000	2.070E+00	6.113E+00	1.710E+01	4.605E+01	1.237E+02	3.405E+02	9.763E+02	2.953E+03	9.746E+03	3.838E+04
6000	2.576E+00	7.998E+00	2.414E+01	6.947E+01	1.911E+02	5.185E+02	1.439E+03	4.204E+03	1.333E+04	5.005E+04
7000	3.027E+00	9.515E+00	2.956E+01	8.940E+01	2.586E+02	7.193E+02	1.998E+03	5.788E+03	1.795E+04	6.395E+04
8000	3.469E+00	1.094E+01	3.432E+01	1.062E+02	3.186E+02	9.175E+02	2.592E+03	7.571E+03	2.346E+04	7.977E+04
9000	3.916E+00	1.235E+01	3.885E+01	1.214E+02	3.721E+02	1.102E+03	3.182E+03	9.419E+03	2.960E+04	9.697E+04
10000	4.379E+00	1.378E+01	4.336E+01	1.360E+02	4.217E+02	1.274E+03	3.751E+03	1.125E+04	3.616E+04	1.163E+05
11000	4.876E+00	1.527E+01	4.795E+01	1.505E+02	4.691E+02	1.436E+03	4.295E+03	1.303E+04	4.285E+04	1.380E+05
12000	5.428E+00	1.685E+01	5.269E+01	1.651E+02	5.159E+02	1.592E+03	4.818E+03	1.475E+04	4.936E+04	1.612E+05
13000	6.061E+00	1.859E+01	5.771E+01	1.802E+02	5.630E+02	1.745E+03	5.331E+03	1.643E+04	5.559E+04	1.861E+05
14000	6.799E+00	2.054E+01	6.311E+01	1.960E+02	6.107E+02	1.896E+03	5.827E+03	1.804E+04	6.143E+04	2.132E+05
15000	7.563E+00	2.274E+01	6.900E+01	2.126E+02	6.600E+02	2.048E+03	6.329E+03	1.966E+04	6.700E+04	2.418E+05
16000	8.659E+00	2.523E+01	7.549E+01	2.304E+02	7.112E+02	2.203E+03	6.832E+03	2.124E+04	7.226E+04	2.714E+05
18000	1.100E+01	3.116E+01	9.056E+01	2.701E+02	8.215E+02	2.524E+03	7.760E+03	2.451E+04	8.232E+04	
20000	1.361E+01	3.819E+01	1.085E+02	3.163E+02	9.445E+02	2.866E+03	8.734E+03	2.809E+04		
22000	1.619E+01	4.581E+01	1.289E+02	3.689E+02	1.081E+03	3.234E+03	9.720E+03			
24000	1.858E+01	5.350E+01	1.509E+02	4.270E+02	1.232E+03	3.628E+03	1.073E+04			

PRESSURE (BARS) OF 0.99 WATER + 0.01 AIR + 7.2E-5 NACL

LOG10 OF DENSITY RATIO (STANDARD DENSITY = 1.0000E+00 GM/CM3)

TEMP, (DEG K)	-4.50	-4.00	-3.50	-3.00	-2.50	-2.00	-1.50	-1.00	-.50	0.00	.50
630	9.149E-02	2.892E-01	9.137E-01	2.880E+00	9.012E+00	2.755E+01	7.768E+01	1.511E+02			
794	1.152E-01	3.642E-01	1.151E+00	3.633E+00	1.142E+01	3.546E+01	1.055E+02	2.676E+02			
999	1.450E-01	4.586E-01	1.450E+00	4.580E+00	1.444E+01	4.520E+01	1.384E+02	3.924E+02	7.882E+02		
1258	1.826E-01	5.774E-01	1.825E+00	5.770E+00	1.822E+01	5.733E+01	1.785E+02	5.368E+02	1.420E+03	1.717E+03	
1584	2.299E-01	7.270E-01	2.299E+00	7.268E+00	2.297E+01	7.253E+01	2.282E+02	7.104E+02	2.134E+03	5.620E+03	6.498E+03
1995	2.903E-01	9.180E-01	2.900E+00	9.163E+00	2.897E+01	9.162E+01	2.902E+02	9.225E+02	2.966E+03	9.873E+03	2.615E+04
2511	3.828E-01	1.190E+00	3.721E+00	1.168E+01	3.679E+01	1.162E+02	3.683E+02	1.181E+03	3.916E+03	1.421E+04	6.323E+04
3162	6.160E-01	1.764E+00	5.216E+00	1.579E+01	4.856E+01	1.511E+02	4.765E+02	1.538E+03	5.276E+03	2.098E+04	1.099E+05
3981	1.288E+00	3.418E+00	9.136E+00	2.519E+01	7.203E+01	2.129E+02	6.490E+02	2.057E+03	7.038E+03	2.853E+04	
5011	2.078E+00	6.145E+00	1.721E+01	4.636E+01	1.244E+02	3.421E+02	9.799E+02	2.962E+03	9.773E+03	3.848E+04	
6309	2.719E+00	8.489E+00	2.596E+01	7.618E+01	2.129E+02	5.801E+02	1.604E+03	4.656E+03	1.462E+04	5.402E+04	
7943	3.444E+00	1.086E+01	3.407E+01	1.054E+02	3.160E+02	9.089E+02	2.563E+03	7.464E+03	2.305E+04	7.858E+04	
9999	4.379E+00	1.378E+01	4.337E+01	1.361E+02	4.223E+02	1.278E+03	3.766E+03	1.128E+04	3.608E+04	1.156E+05	
12589	5.790E+00	1.786E+01	5.562E+01	1.740E+02	5.440E+02	1.686E+03	5.144E+03	1.582E+04	5.316E+04	1.747E+05	
15848	8.500E+00	2.483E+01	7.448E+01	2.277E+02	7.038E+02	2.183E+03	6.785E+03	2.114E+04	7.182E+04	2.668E+05	
19952	1.355E+01	3.801E+01	1.081E+02	3.152E+02	9.418E+02	2.862E+03	8.738E+03	2.818E+04			
25118	1.983E+01	5.769E+01	1.634E+02	4.613E+02	1.321E+03	3.862E+03	1.132E+04				
31622	2.643E+01	7.984E+01	2.347E+02	6.702E+02	1.883E+03	5.333E+03	1.510E+04				
39810	3.586E+01	1.070E+02	3.193E+02	9.307E+02	2.633E+03	7.376E+03	2.063E+04				
50118	4.855E+01	1.467E+02	4.363E+02	1.273E+03	3.619E+03	1.011E+04	2.811E+04	7.121E+04			
63095	6.523E+01	1.971E+02	5.924E+02	1.745E+03	4.987E+03	1.390E+04	3.829E+04	9.983E+04			
79432	8.906E+01	2.690E+02	8.040E+02	2.372E+03	6.846E+03	1.918E+04	5.249E+04	1.356E+05			
99999	1.218E+02	3.663E+02	1.097E+03	3.242E+03	9.395E+03	2.645E+04	7.220E+04	1.816E+05			
125892	1.671E+02	5.025E+02	1.502E+03	4.435E+03	1.289E+04	3.648E+04	9.958E+04	2.431E+05			
158489	2.289E+02	6.895E+02	2.060E+03	6.085E+03	1.771E+04	5.032E+04	1.377E+05	3.322E+05			
199526	3.064E+02	9.350E+02	2.810E+03	8.334E+03	2.432E+04	6.939E+04	1.907E+05	4.685E+05			
251188	3.939E+02	1.225E+03	3.753E+03	1.128E+04	3.320E+04	9.535E+04	2.642E+05	6.714E+05			
316227	4.994E+02	1.564E+03	4.858E+03	1.487E+04	4.454E+04	1.297E+05	3.643E+05	9.587E+05	1.745E+06		
398107	6.311E+02	1.983E+03	6.199E+03	1.919E+04	5.844E+04	1.734E+05	4.964E+05	1.348E+06	3.199E+06		
501187	7.980E+02	2.509E+03	7.869E+03	2.452E+04	7.551E+04	2.278E+05	6.656E+05	1.859E+06	4.815E+06	9.317E+06	
630957	1.044E+03	3.223E+03	1.003E+04	3.125E+04	9.682E+04	2.956E+05	8.792E+05	2.515E+06	6.802E+06	1.653E+07	2.040E+07
794328	1.414E+03	4.349E+03	1.334E+04	4.081E+04	1.251E+05	3.823E+05	1.150E+06	3.354E+06	9.332E+06	2.448E+07	5.242E+07
999999	1.871E+03	5.832E+03	1.797E+04	5.496E+04	1.673E+05	5.055E+05	1.514E+06	4.450E+06	1.261E+07	3.417E+07	8.612E+07
1258925	2.373E+03	7.479E+03	2.347E+04	7.304E+04	2.242E+05	6.793E+05	2.032E+06	5.970E+06	1.704E+07	4.683E+07	1.241E+08
1584893	2.991E+03	9.444E+03	2.978E+04	9.358E+04	2.922E+05	9.006E+05	2.724E+06	8.054E+06	2.317E+07	6.421E+07	1.730E+08
1995262	3.767E+03	1.190E+04	3.757E+04	1.184E+05	3.719E+05	1.160E+06	3.572E+06	1.075E+07	3.136E+07	8.796E+07	2.396E+08
2511886	4.745E+03	1.499E+04	4.736E+04	1.494E+05	4.705E+05	1.475E+06	4.588E+06	1.403E+07	4.177E+07	1.193E+08	3.295E+08
3162277	5.975E+03	1.888E+04	5.967E+04	1.884E+05	5.940E+05	1.868E+06	5.840E+06	1.805E+07	5.463E+07	1.593E+08	4.474E+08
3981071	7.523E+03	2.378E+04	7.516E+04	2.374E+05	7.492E+05	2.360E+06	7.405E+06	2.304E+07	7.057E+07	2.095E+08	5.965E+08
5011872	9.472E+03	2.995E+04	9.466E+04	2.991E+05	9.445E+05	2.978E+06	9.367E+06	2.929E+07	9.046E+07	2.723E+08	7.905E+08
6309573	1.193E+04	3.770E+04	1.192E+05	3.767E+05	1.190E+06	3.756E+06	1.183E+07	3.712E+07	1.154E+08	3.513E+08	1.034E+09
7943282	1.501E+04	4.747E+04	1.501E+05	4.744E+05	1.499E+06	4.735E+06	1.493E+07	4.695E+07	1.466E+08	4.506E+08	1.343E+09
9999999	1.890E+04	5.977E+04	1.890E+05	5.974E+05	1.888E+06	5.966E+06	1.883E+07	5.930E+07	1.859E+08	5.763E+08	1.735E+09
12589254	2.380E+04	7.525E+04	2.379E+05	7.523E+05	2.378E+06	7.515E+06	2.373E+07	7.483E+07	2.351E+08	7.319E+08	2.229E+09
15848931	2.996E+04	9.474E+04	2.996E+05	9.472E+05	2.994E+06	9.465E+06	2.990E+07	9.436E+07	2.970E+08	9.286E+08	2.852E+09

ENERGY (ERG/GM) OF 0.99 WATER + 0.01 AIR + 7.2E-5 NACL

LOG10 OF DENSITY RATIO (STANDARD DENSITY = 1.0000E+00 GM/CM3)

TEMP, (DEG K)	-4.50	-4.00	-3.50	-3.00	-2.50	-2.00	-1.50	-1.00	-.50	0.00
1000	1.513E+10	1.513E+10	1.513E+10	1.511E+10	1.507E+10	1.495E+10	1.455E+10	1.328E+10	9.288E+09	
2000	3.740E+10	3.689E+10	3.656E+10	3.634E+10	3.619E+10	3.603E+10	3.576E+10	3.502E+10	3.278E+10	2.572E+10
3000	1.234E+11	1.006E+11	8.630E+10	7.724E+10	7.140E+10	6.755E+10	6.487E+10	6.265E+10	5.980E+10	5.369E+10
4000	4.095E+11	3.191E+11	2.438E+11	1.898E+11	1.537E+11	1.295E+11	1.142E+11	1.032E+11	9.430E+10	8.456E+10
5000	5.763E+11	5.315E+11	4.580E+11	3.727E+11	2.965E+11	2.377E+11	1.947E+11	1.632E+11	1.390E+11	1.190E+11
6000	6.237E+11	6.107E+11	5.794E+11	5.207E+11	4.413E+11	3.615E+11	2.933E+11	2.375E+11	1.918E+11	1.568E+11
7000	6.511E+11	6.465E+11	6.343E+11	6.044E+11	5.480E+11	4.716E+11	3.925E+11	3.192E+11	2.515E+11	1.980E+11
8000	6.764E+11	6.734E+11	6.674E+11	6.523E+11	6.174E+11	5.567E+11	4.801E+11	4.000E+11	3.158E+11	2.414E+11
9000	7.153E+11	7.003E+11	6.953E+11	6.861E+11	6.643E+11	6.198E+11	5.527E+11	4.742E+11	3.818E+11	2.858E+11
10000	7.430E+11	7.318E+11	7.241E+11	7.159E+11	7.007E+11	6.680E+11	6.120E+11	5.397E+11	4.477E+11	3.323E+11
11000	7.961E+11	7.720E+11	7.574E+11	7.466E+11	7.331E+11	7.077E+11	6.615E+11	5.970E+11	5.115E+11	3.809E+11
12000	8.722E+11	8.254E+11	7.986E+11	7.812E+11	7.660E+11	7.438E+11	7.047E+11	6.475E+11	5.716E+11	4.315E+11
13000	9.790E+11	8.988E+11	8.513E+11	8.225E+11	8.020E+11	7.797E+11	7.452E+11	6.943E+11	6.281E+11	4.843E+11
14000	1.122E+12	9.953E+11	9.189E+11	8.729E+11	8.431E+11	8.174E+11	7.844E+11	7.378E+11	6.807E+11	5.414E+11
15000	1.305E+12	1.119E+12	1.004E+12	9.349E+11	8.915E+11	8.594E+11	8.263E+11	7.823E+11	7.324E+11	6.036E+11
16000	1.523E+12	1.271E+12	1.110E+12	1.010E+12	9.486E+11	9.068E+11	8.717E+11	8.285E+11	7.838E+11	6.730E+11
18000	2.033E+12	1.692E+12	1.381E+12	1.205E+12	1.094E+12	1.023E+12	9.771E+11	9.395E+11	9.039E+11	
20000	2.547E+12	2.093E+12	1.721E+12	1.456E+12	1.281E+12	1.176E+12	1.115E+12	1.095E+12		
22000	2.977E+12	2.530E+12	2.095E+12	1.749E+12	1.508E+12	1.364E+12	1.282E+12			
24000	3.297E+12	2.912E+12	2.464E+12	2.061E+12	1.767E+12	1.579E+12	1.472E+12			

ENERGY (ERG/GM) OF 0.99 WATER + 0.01 AIR + 7.2E-5 NACL

LOG10 OF DENSITY RATIO (STANDARD DENSITY = 1.0000E+00 GM/CM3)

TEMP. (DEG K)	-4.50	-4.00	-3.50	-3.00	-2.50	-2.00	-1.50	-1.00	-.50	0.00	.50
630	8.944E+09	8.942E+09	8.934E+09	8.909E+09	8.832E+09	8.586E+09	7.810E+09	5.354E+09			
794	1.157E+10	1.157E+10	1.156E+10	1.155E+10	1.149E+10	1.133E+10	1.079E+10	9.106E+09			
999	1.513E+10	1.513E+10	1.513E+10	1.511E+10	1.507E+10	1.495E+10	1.455E+10	1.328E+10	7.286E+09		
1258	2.002E+10	2.002E+10	2.001E+10	2.000E+10	1.997E+10	1.967E+10	1.955E+10	1.855E+10	1.537E+10	5.343E+09	
1584	2.678E+10	2.676E+10	2.674E+10	2.673E+10	2.670E+10	2.661E+10	2.635E+10	2.552E+10	2.291E+10	1.464E+10	
1995	3.724E+10	3.675E+10	3.643E+10	3.622E+10	3.607E+10	3.592E+10	3.564E+10	3.491E+10	3.266E+10	2.559E+10	3.245E+09
2511	6.231E+10	5.736E+10	5.419E+10	5.212E+10	5.075E+10	4.980E+10	4.903E+10	4.809E+10	4.610E+10	4.041E+10	2.282E+10
3162	1.571E+11	1.236E+11	1.025E+11	8.909E+10	8.053E+10	7.495E+10	7.113E+10	6.815E+10	6.481E+10	5.846E+10	4.146E+10
3981	4.027E+11	3.137E+11	2.405E+11	1.880E+11	1.526E+11	1.293E+11	1.137E+11	1.027E+11	9.389E+10	8.413E+10	0.
5011	5.774E+11	5.334E+11	4.604E+11	3.748E+11	2.980E+11	2.385E+11	1.952E+11	1.635E+11	1.393E+11	1.192E+11	0.
6309	6.330E+11	6.240E+11	6.010E+11	5.528E+11	4.792E+11	3.975E+11	3.237E+11	2.612E+11	2.087E+11	1.687E+11	0.
7943	6.749E+11	6.720E+11	6.659E+11	6.504E+11	6.147E+11	5.527E+11	4.747E+11	3.936E+11	3.099E+11	2.375E+11	0.
9999	7.430E+11	7.318E+11	7.242E+11	7.161E+11	7.011E+11	6.686E+11	6.121E+11	5.380E+11	4.440E+11	3.280E+11	0.
12589	9.310E+11	8.663E+11	8.281E+11	8.046E+11	7.869E+11	7.650E+11	7.294E+11	6.750E+11	6.021E+11	4.563E+11	0.
15848	1.488E+12	1.246E+12	1.092E+12	9.980E+11	9.397E+11	8.999E+11	8.659E+11	8.228E+11	7.761E+11	6.580E+11	0.
19952	2.536E+12	2.082E+12	1.712E+12	1.449E+12	1.276E+12	1.172E+12	1.113E+12	1.095E+12			
25118	3.437E+12	3.094E+12	2.658E+12	2.236E+12	1.919E+12	1.711E+12	1.597E+12				
31622	4.026E+12	3.819E+12	3.520E+12	3.128E+12	2.745E+12	2.438E+12	2.221E+12				
39810	5.176E+12	4.700E+12	4.323E+12	3.950E+12	3.554E+12	3.191E+12	2.895E+12				
50118	6.742E+12	6.256E+12	5.671E+12	5.076E+12	4.520E+12	4.033E+12	3.648E+12	3.303E+12			
63095	8.753E+12	7.973E+12	7.336E+12	6.670E+12	5.932E+12	5.211E+12	4.643E+12	4.199E+12			
79432	1.186E+13	1.083E+13	9.759E+12	8.747E+12	7.793E+12	6.809E+12	6.021E+12	5.399E+12			
99999	1.627E+13	1.462E+13	1.316E+13	1.181E+13	1.048E+13	9.170E+12	7.965E+12	7.094E+12			
125892	2.232E+13	2.007E+13	1.800E+13	1.603E+13	1.418E+13	1.241E+13	1.071E+13	9.441E+12			
158489	3.015E+13	2.733E+13	2.452E+13	2.181E+13	1.927E+13	1.685E+13	1.453E+13	1.258E+13			
199526	3.796E+13	3.565E+13	3.258E+13	2.927E+13	2.595E+13	2.272E+13	1.959E+13	1.663E+13	1.858E+12		
251188	4.332E+13	4.239E+13	4.057E+13	3.767E+13	3.400E+13	3.004E+13	2.598E+13	2.175E+13	1.010E+13		
316227	4.855E+13	4.809E+13	4.715E+13	4.535E+13	4.239E+13	3.833E+13	3.354E+13	2.806E+13	1.862E+13		
398107	5.488E+13	5.453E+13	5.390E+13	5.269E+13	5.052E+13	4.699E+13	4.203E+13	3.570E+13	2.688E+13	6.543E+12	
501187	6.366E+13	6.281E+13	6.208E+13	6.106E+13	5.931E+13	5.629E+13	5.155E+13	4.485E+13	3.578E+13	1.975E+13	
630957	9.166E+13	8.119E+13	7.508E+13	7.252E+13	7.023E+13	6.729E+13	6.274E+13	5.592E+13	4.603E+13	3.315E+13	4.277E+12
794328	1.457E+14	1.301E+14	1.152E+14	1.004E+14	9.044E+13	8.358E+13	7.757E+13	7.011E+13	5.990E+13	4.714E+13	2.513E+13
999999	1.955E+14	1.870E+14	1.719E+14	1.538E+14	1.360E+14	1.191E+14	1.046E+14	9.218E+13	7.904E+13	6.456E+13	4.634E+13
1258925	2.233E+14	2.219E+14	2.183E+14	2.098E+14	1.943E+14	1.738E+14	1.525E+14	1.317E+14	1.109E+14	9.043E+13	7.033E+13
1584893	2.530E+14	2.525E+14	2.515E+14	2.491E+14	2.436E+14	2.318E+14	2.122E+14	1.870E+14	1.593E+14	1.302E+14	1.032E+14
1995262	2.899E+14	2.896E+14	2.890E+14	2.878E+14	2.854E+14	2.800E+14	2.689E+14	2.490E+14	2.200E+14	1.842E+14	1.487E+14
2511886	3.363E+14	3.360E+14	3.356E+14	3.347E+14	3.330E+14	3.297E+14	3.229E+14	3.093E+14	2.854E+14	2.489E+14	2.070E+14
3162277	3.946E+14	3.944E+14	3.940E+14	3.933E+14	3.919E+14	3.893E+14	3.842E+14	3.740E+14	3.547E+14	3.212E+14	2.765E+14
3981071	4.681E+14	4.679E+14	4.675E+14	4.669E+14	4.657E+14	4.639E+14	4.592E+14	4.507E+14	4.342E+14	4.036E+14	3.582E+14
5011872	5.605E+14	5.604E+14	5.601E+14	5.595E+14	5.585E+14	5.565E+14	5.528E+14	5.454E+14	5.308E+14	5.022E+14	4.560E+14
6309573	6.769E+14	6.768E+14	6.765E+14	6.760E+14	6.751E+14	6.734E+14	6.701E+14	6.636E+14	6.504E+14	6.235E+14	5.762E+14
7943282	8.234E+14	8.233E+14	8.231E+14	8.226E+14	8.218E+14	8.203E+14	8.174E+14	8.116E+14	7.997E+14	7.744E+14	7.262E+14
9999999	1.008E+15	1.008E+15	1.008E+15	1.007E+15	1.006E+15	1.005E+15	1.002E+15	9.973E+14	9.866E+14	9.630E+14	9.145E+14
12589254	1.240E+15	1.240E+15	1.240E+15	1.239E+15	1.239E+15	1.238E+15	1.235E+15	1.231E+15	1.221E+15	1.199E+15	1.151E+15
15848931	1.532E+15	1.532E+15	1.532E+15	1.532E+15	1.531E+15	1.530E+15	1.528E+15	1.524E+15	1.515E+15	1.495E+15	1.449E+15

ELECTRON DENSITY (ELECTRONICS/CM3) IN 0.99 WATER + 0.01 AIR + 7.2E-5 NACL

LOG10 OF DENSITY RATIO (STANDARD DENSITY = 1.0000E+00 GM/CM3)

TEMP. (DEG K)	-4.50	-4.00	-3.50	-3.00	-2.50	-2.00	-1.50	-1.00	-.50	0.00	.50
631	2.921E-17	2.189E-17	1.637E-17	1.217E-17	8.885E-18	6.161E-18	3.763E-18	1.809E-18	5.993E-19	9.534E-20	1.057E-21
794	3.472E-09	2.604E-09	1.953E-09	1.464E-09	1.098E-09	8.232E-10	6.142E-10	4.360E-10	2.077E-10	2.903E-11	2.721E-13
999	9.392E-03	7.043E-03	5.282E-03	3.962E-03	2.974E-03	2.238E-03	1.694E-03	1.300E-03	9.307E-04	1.850E-04	1.418E-06
1258	1.261E+03	9.458E+02	7.094E+02	5.320E+02	3.992E+02	2.998E+02	2.260E+02	1.721E+02	1.319E+02	4.750E+01	3.855E-01
1584	1.509E+07	1.154E+07	8.731E+06	6.570E+06	4.933E+06	3.701E+06	2.776E+06	2.083E+06	1.546E+06	7.246E+05	8.131E+03
1995	1.421E+10	1.422E+10	1.272E+10	1.054E+10	8.345E+09	6.420E+09	4.843E+09	3.570E+09	2.444E+09	9.049E+08	1.477E+07
2511	8.046E+11	1.137E+12	1.415E+12	1.541E+12	1.489E+12	1.308E+12	1.064E+12	7.902E+11	4.796E+11	1.472E+11	4.665E+09
3162	1.201E+13	2.008E+13	2.981E+13	3.865E+13	4.316E+13	4.223E+13	3.717E+13	2.933E+13	1.889E+13	6.908E+12	5.909E+11
3981	5.594E+13	1.268E+14	2.425E+14	3.874E+14	5.114E+14	5.638E+14	5.377E+14	4.533E+14	3.188E+14	1.412E+14	
5011	8.154E+13	2.528E+14	6.228E+14	1.435E+15	2.627E+15	3.719E+15	4.201E+15	3.984E+15	3.161E+15	1.835E+15	
6309	2.991E+14	6.624E+14	1.526E+15	3.437E+15	7.091E+15	1.259E+16	1.848E+16	2.243E+16	2.301E+16	2.105E+16	
7943	3.571E+15	6.464E+15	1.187E+16	2.219E+16	4.119E+16	7.107E+16	1.078E+17	1.439E+17	1.764E+17	2.137E+17	
9999	3.281E+16	5.909E+16	1.065E+17	1.918E+17	3.414E+17	5.739E+17	8.844E+17	1.215E+18	1.525E+18	1.917E+18	
12589	1.976E+17	3.631E+17	6.667E+17	1.226E+18	2.254E+18	4.088E+18	6.552E+18	9.530E+18	1.231E+19	1.552E+19	
15848	7.835E+17	1.576E+18	2.926E+18	5.601E+18	1.081E+19	2.117E+19	3.825E+19	6.418E+19	9.272E+19	1.195E+20	
19952	1.883E+18	4.217E+18	8.901E+18	1.831E+19	3.779E+19	8.068E+19	1.939E+20	5.928E+20			
25118	2.705E+18	7.264E+18	1.789E+19	4.136E+19	9.270E+19	2.141E+20	5.796E+20				
31622	3.021E+18	8.899E+18	2.489E+19	6.481E+19	1.578E+20	3.840E+20	1.040E+21				
39810	3.456E+18	1.004E+19	2.904E+19	8.067E+19	2.091E+20	5.253E+20	1.385E+21				
50118	3.985E+18	1.180E+19	3.407E+19	9.528E+19	2.535E+20	6.475E+20	1.675E+21	5.712E+21			
63095	4.457E+18	1.320E+19	3.001E+19	1.120E+20	3.058E+20	7.944E+20	2.043E+21	6.350E+21			
79432	5.098E+18	1.514E+19	4.440E+19	1.281E+20	3.593E+20	9.631E+20	2.507E+21	7.605E+21			
99999	5.810E+18	1.718E+19	5.085E+19	1.473E+20	4.189E+20	1.150E+21	3.065E+21	9.476E+21			
125892	6.611E+18	1.961E+19	5.785E+19	1.686E+20	4.838E+20	1.356E+21	3.718E+21	1.171E+22	7.602E+22		
158489	7.464E+18	2.226E+19	6.580E+19	1.925E+20	5.562E+20	1.580E+21	4.442E+21	1.398E+22	7.263E+22		
199526	8.119E+18	2.469E+19	7.379E+19	2.177E+20	6.338E+20	1.819E+21	5.190E+21	1.601E+22	7.041E+22	2.279E+23	
251188	8.323E+18	2.594E+19	7.969E+19	2.399E+20	7.083E+20	2.056E+21	5.918E+21	1.778E+22	6.796E+22	2.197E+23	
316227	8.374E+18	2.631E+19	8.212E+19	2.530E+20	7.645E+20	2.258E+21	6.557E+21	1.929E+22	6.476E+22	2.156E+23	6.860E+23
398107	8.395E+18	2.645E+19	8.303E+19	2.587E+20	7.956E+20	2.396E+21	7.049E+21	2.057E+22	6.311E+22	2.115E+23	6.703E+23
501187	8.431E+18	2.655E+19	8.350E+19	2.615E+20	8.120E+20	2.481E+21	7.401E+21	2.165E+22	6.366E+22	2.041E+23	6.627E+23
630957	8.873E+18	2.724E+19	8.460E+19	2.642E+20	8.229E+20	2.536E+21	7.658E+21	2.257E+22	6.537E+22	1.972E+23	6.506E+23
794328	9.790E+18	2.989E+19	9.105E+19	2.768E+20	8.464E+20	2.596E+21	7.882E+21	2.341E+22	6.766E+22	1.961E+23	6.238E+23
999999	1.044E+19	3.246E+19	9.955E+19	3.026E+20	9.158E+20	2.757E+21	8.260E+21	2.447E+22	7.075E+22	2.011E+23	6.036E+23
1258925	1.053E+19	3.321E+19	1.043E+20	3.243E+20	9.932E+20	2.998E+21	8.946E+21	2.631E+22	7.574E+22	2.127E+23	6.136E+23
1584893	1.054E+19	3.331E+19	1.051E+20	3.309E+20	1.035E+21	3.195E+21	9.666E+21	2.860E+22	8.267E+22	2.316E+23	6.533E+23
1995262	1.055E+19	3.333E+19	1.053E+20	3.323E+20	1.046E+21	3.274E+21	1.012E+22	3.057E+22	8.968E+22	2.535E+23	7.106E+23
2511886	1.055E+19	3.335E+19	1.054E+20	3.328E+20	1.050E+21	3.301E+21	1.031E+22	3.170E+22	9.499E+22	2.735E+23	7.697E+23
3162277	1.055E+19	3.335E+19	1.054E+20	3.331E+20	1.052E+21	3.314E+21	1.039E+22	3.228E+22	9.827E+22	2.885E+23	8.202E+23
3981071	1.055E+19	3.336E+19	1.055E+20	3.333E+20	1.053E+21	3.321E+21	1.044E+22	3.262E+22	1.003E+23	2.992E+23	8.604E+23
5011872	1.055E+19	3.336E+19	1.055E+20	3.334E+20	1.053E+21	3.326E+21	1.048E+22	3.284E+22	1.018E+23	3.072E+23	8.931E+23
6309573	1.055E+19	3.336E+19	1.055E+20	3.335E+20	1.054E+21	3.329E+21	1.050E+22	3.300E+22	1.028E+23	3.135E+23	9.213E+23
7943282	1.055E+19	3.336E+19	1.055E+20	3.335E+20	1.054E+21	3.331E+21	1.052E+22	3.310E+22	1.036E+23	3.184E+23	9.462E+23
9999999	1.055E+19	3.337E+19	1.055E+20	3.336E+20	1.055E+21	3.333E+21	1.053E+22	3.318E+22	1.041E+23	3.223E+23	9.683E+23
12589254	1.055E+19	3.337E+19	1.055E+20	3.336E+20	1.055E+21	3.334E+21	1.053E+22	3.324E+22	1.045E+23	3.253E+23	9.873E+23
15848931	1.055E+19	3.337E+19	1.055E+20	3.336E+20	1.055E+21	3.335E+21	1.054E+22	3.327E+22	1.048E+23	3.276E+23	1.003E+24

A.10 A COMPARISON OF CARBON DIOXIDE AND WATER AS THE ENERGY ABSORBING MEDIUM FOR POWER GENERATION FROM THERMONUCLEAR EXPLOSIONS (S. Ridgway)

One of the proposed materials for thermonuclear energy absorption in the Pacer electric power generation program is carbon dioxide. For various reasons connected with the overall thermal efficiency of the plant steam has been the preferred energy absorbing substance. The solubility of salt in condensed steam, water, is large, and the consequent possibility of appreciable attack on the wall of the salt cavity if the steam is cooled enough to allow its condensation into a salt-water liquid phase suggest that the merits of other fluids without this disadvantage be explored.

Some desireable properties of a suitable fluid are:

1. High specific heat.
2. Neutrality toward common and inexpensive materials of construction.
3. Condensible
4. Very low cost.
5. Opacity sufficient to absorb the fireball radiation.

Steam meets these criteria admirably (with a little air added to give opacity) except for #2. High temperature steam is somewhat corrosive toward steel, but many generations of experience have evolved steels and operating procedures that keep the corrosion under control. It is the corrosiveness toward the cavity that is the question. However we will leave the question of the corrosiveness for the present, and examine how good steam is from the thermodynamic point of view.

Let us establish a possible set of operating conditions for a steam system to get a basis of comparison with other possible fluids. The cavity temperature + pressure are chosen to be 520°C, and 240 bars. From the 1969 Edition of Keenan and Keyes Steam Tables we extract a few pertinent values.

Pressure = 240 bars

Temperature	Specific Volume	Specific enthalpy	Specific entropy
520°C	12.414 cm^3/gm	3248.5 j/gm	6.0842 j/gm °K
380	2.609	2024.8	4.3068

Suppose that the steam is cooled to 380°C in the course of its supplying heat to an ideal reversible thermal power plant that rejects heat to a cold reservoir at 323°K, which temperature corresponds to a steam condenser pressure of 4" Hg. The entropy content of the steam drops by 1.7774 j/gm deg in the course of its giving up its heat to the ideal power plant. This entropy must be delivered to the cold reservoir, thus the heat rejected to the cold reservoir would be $T_c(s_1 - s_2)$ which is 574.1 joules/gram. The ideal thermal efficiency is then:

$$\frac{h_1 - h_2 - T_c(s_1 - s_2)}{h_1 - h_2} = .5307$$

Allowing for losses due to irreversible processes in turbines and heat exchangers the net thermal efficiency might be 0.4. Then the mass flow required for a 2,000 megawatt electric plant is $4. \times 10^6$ grams/sec. The specific volume of the 380°C steam is about 1/5 of that of the 520°C steam, and could be easily returned to the cavity by its own weight. The net pressure force available due to density difference in the up pipe and the down pipe available to drive the steam around the circuit is about 27 bars, so that no real pump is needed to circulate the steam. This suggests a natural convection design that uses two up pipes and one down pipe each 3 feet in diameter. From Perry's Chemical Engineers Handbook, Section 5, p. 24, fourth edition, we have:

$$P_1 - P_2 = \frac{fLG^2}{2\, g_c\, \rho_{av}\, R_H} \qquad R_H = D/4$$

for the pressure drop in a pipe of length L, friction factor f, diameter D for the flow of a fluid of average density ρ_{av} at a mass flow rate of G

G up = 624 lb/ft^2 - sec
$P_1 - P_2$ = 19,200 lb/ft^2 = 9.2 bars
G down = 1248 lb/ft^2 - sec
$P_1 - P_2$ = 16,170 lb/ft^2 = 7.7 bars

The total pressure drop due to friction in the pipes is 16.9 bars, and 27 bars are available from density difference, leaving an excess of 10 for valve and bend losses, and heat exchanger pressure losses.

This convection pumping effect is not free, the pumping work coming from a heat engine that expands the hot steam in the up pipe and compresses the cool steam in the down pipe.

The entropy that is created due to friction in the pipes is:

$$\Delta S = 0.1 \left(\left(\frac{V\Delta P}{T}\right)_{up} + \left(\frac{V\Delta P}{T}\right)_{down} \right) = .01745 \text{ j/gm - dy}$$

where V is the specific volume and ΔP the pressure drop. The factor 0.1 converts from bar - cm^3 to joules.

The additional heat that must be rejected to the cold reservoir as a consequence of the friction losses in the pipes is 5.64 joules per gram. This friction loss drops the ideal thermal efficiency from .531 to .526. Multiplying this reduced value by a factor of .75 to .8 to account for irreversibilities in turbines and heat exchangers indicate the efficiency of a plant that uses steam as the heat absorbing medium in the cavity could have an efficiency between 39 and 42%.

To summarize the steam plant is about 40% efficient and requires 3 pipes of 3' inside diameter for a 2000 megawatt plant, and requires no circulating pump.

Let us do a similiar analysis for carbon dioxide. We will remove the gas from the cavity at 240 bars and 520°C, and return it to the cavity at a temperature of 100°C. Thermodynamic data for 1 gram of material are

Pressure (bars)	T	specific enthalpy	specific entropy	specific volume
240	520°C	511.6 joules/gm	-.0162 joules/gm deg	6.3056 cm^3/gm
240	100°C	-75.24	-1.8068 joules/gm deg	1.63
1	0°C	0.0	0.0	—

The enthalpy drop in the transit of the carbon dioxide through the thermal power plant is 586.8 joules/gm, and the entropy drop is 1.0706 joules/gm deg. From these values, and a heat dump temperature of 50°C we infer an ideal thermal efficiency of

$$\frac{\Delta h - Tc\ \Delta s}{\Delta h} = \frac{586.8 - 345}{586.8} = .412$$

which should be compared with the value of .531 obtained for steam. In this sense carbon dioxide is only 77% as good as steam. We will further find that more pipes are needed to bring the gas from the cavity to the surface and back, since the electrical power output per gram is somewhat less than half of what it is for steam, even though the output per unit volume is nearly the same. The real thermal efficiency can be expected to be about 30%.

The estimated output of a reasonably efficient thermal power plant operating on the hot carbon dioxide gas is about 193 joules per gram. The necessary mass flow to provide for 2000 megawatts electrical is 1. x 10^7 grams per second which is 2.5 times the mass flow required if steam were the heat transport fluid. The molecular weight ratio is 2.44 so approximately equal volumes of gas are transported in the two cases. To have the same pump work for the two plants the pressure drop in the pipes should be the same, so the velocity should be reduced by the square root of 2.44 by increasing the number of pipes. We are thus led to consider a design with three pipes up, and two pipes down. Using three foot inside diameter pipes as we did in the case for steam the up pressure drop turns out to be 9.76 bars, and the down pressure drop is 5.68 bars for a total of 15.44 bars. The head in the up pipe is 14.2 bars, and 55. bars is the head in the down pipe, so that a net of 40.8 bars are available to drive the circulation, and to do work in the plant.

In summary a carbon dioxide plant would be about 3/4 as efficient as a steam plant, and require 50% more piping to bring the heat up but these disadvantages are not overwhelming, and the greater neutrality of carbon dioxide toward salt and steel may well swing the balance in its favor.

A.11 HEATING OF THE SALT CAVITY WALL BY THE THERMAL PULSES FROM THE NUCLEAR EXPLOSIONS (R. Turco and F. Gilmore)

It was suggested in Section A.2 of this appendix that if a 100 kt device is exploded once a day in a salt cavity of 200 m radius, and a few percent of this energy is emitted as a thermal pulse (ultraviolet, visible and infrared radiation) and absorbed in the first few centimeters or meters of the salt, serious changes in the cavity size and shape due to melting may occur after a few hundred bursts. This memo reports the results of a quantitative study of this problem, in which the temperature profile history of the salt is computed numerically.

To calculate the heating of the salt, one needs the energy in each thermal pulse and the absorption coefficient, thermal conductivity and specific heat of the salt. A quantitative value for the thermal pulse energy is available only for a cavity filled with compressed air, where it is much less than 1% of the total explosion energy [1] due to the formation of opaque nitrogen dioxide in the air. For a steam-filled cavity the thermal pulse probably contains on the order of 1% of the explosion energy (see Section A.2), while if carbon dioxide is used it may be a few percent. Accordingly, calculations were made for thermal pulses of 1 and 10 kilotons, corresponding to 1% and 10% of the total yield.

The absorption coefficient of natural salt for the thermal radiation is very uncertain. Probably it depends greatly upon the impurities, grain boundaries and cracks in the salt. Many of these defects cause scattering of the radiation, which increases the effective absorption coefficient by increasing the distance the average photon must travel to penetrate a given distance. In the present calculations, three effective absorption mean free paths, 0.01, 0.1 and 1 m, were chosen to cover the range of probable values, and the energy of each thermal pulse was deposited with a corresponding exponential decrease with distance.

For a given energy deposition, the temperature rise of the salt depends upon the product $C\rho$, where C is the specific heat per unit mass and ρ is the density. For the present work, the specific heat was obtained as a function of temperature from the JANAF tables [2]. The density was calculated from the density at 300°K, 2.16 g/cm^3, and linear expansion tabulated in the AIP Handbook [3]. The product was then fit by the expression

$$C\rho = 4.48 \times 10^5 + 44(T-300) + 0.090(T-300)^2 \ \mathrm{cal/(m^3 \cdot {}^\circ K)},$$

which is accurate to about 1% between 300 and 1100°K.

The cooling rate of the salt depends upon its thermal conductivity, K. Data for the conductivity of natural salt between 400 and 900°K were taken from Stephens and Maimoni [4] and fit to within 7% by an expression whose form was suggested by the authors:

$$K = 390/(T-100) + 8.7 \times 10^{-10}\, T^3 \ \mathrm{cal/(m \cdot {}^\circ K \cdot sec)}.$$

The heat conduction in the salt was calculated by approximating the differential equation by difference equations and using a spatial grid with a spacing that increased with increasing distance from the wall. An initial salt temperature of 300°K was assumed, while the cavity wall was assumed to emit black-body radiation at its local temperature, and absorb steady 800°K radiation from the cavity gas. This radiative boundary condition is justified by the opacity of both the salt and the gas at the longer infrared wavelengths.

Figs. 1 to 3 show the calculated temperature history of the salt near the wall, for 1 KT thermal pulses absorbed exponentially with a 1/e distance of 0.01, 0.1 and 1 m, respectively. Each curve plotted corresponds to a time immediately after the daily explosion, so it represents the maximum temperature for that day. Fig. 1, for the shortest deposition distance, shows that after a few days about half a centimeter of salt exceeds the melting temperature of 1073°K. The curves for later times underestimate the melting because they assume that the original salt at the wall continues to shield the deeper layers from the thermal pulse, while actually successive layers will melt and flow away. In 1000 days (about 3 years) over a meter of salt will be melted,so the problem may be significant.

Figs. 2 and 3, for longer absorption mean free paths, show little heating above the 800°K steady cavity temperature, and hence no salt melting problem.

Figs. 4 to 6, for ten times as strong a thermal pulse, show serious melting for 0.01 and 0.1 m absorption distances, and no melting for the 1 m absorption distance.

We conclude that if the salt is quite pure and transparent there is no melting problem, but if the salt is moderately "dirty" and opaque (absorption mean free path much less than a meter) the gas in the cavity should be chosen to minimize the thermal pulse.

REFERENCES

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3. Amer. Inst. Phys. Handbook, 3rd Ed., McGraw-Hill, New York, 1972, p. 4-139.
4. D. R. Stephens and A. Maimoni, "Thermal Conductivity of Rock Salt," U. C. Lawrence Radiation Lab., Report UCRL-6894, Rev. II, Feb. 1964.

Fig. 1. HEATING OF A SALT CAVITY BY A DAILY 1 KT THERMAL PULSE ABSORBED IN .01 METERS. THE TEMPERATURE CURVES CORRESPOND TO 0.1.10.100.200.ETC., PULSES.

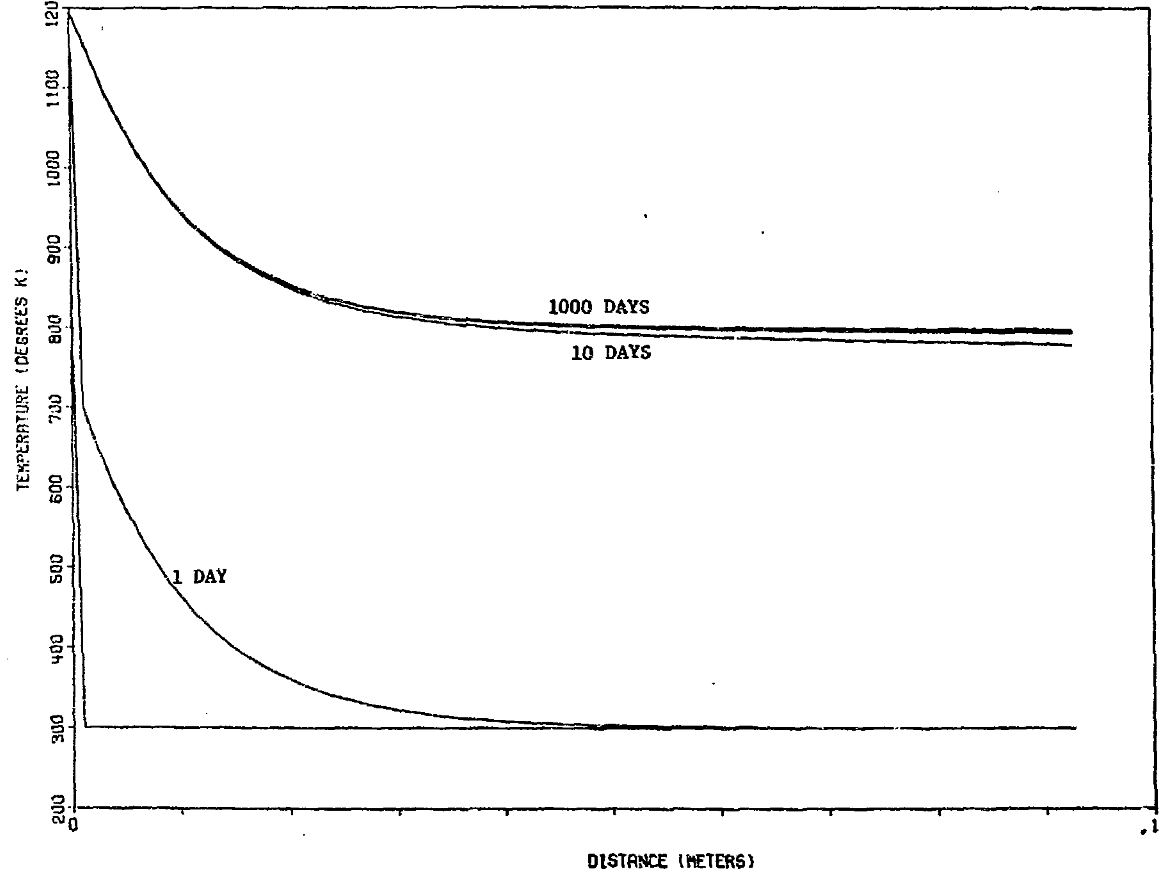


Fig. 2. HEATING OF A SALT CAVITY BY A DAILY 1 KT THERMAL PULSE ABSORBED IN 0.1 METERS. THE TEMPERATURE CURVES CORRESPOND TO 0.1.10.100.200.ETC.. PULSES.

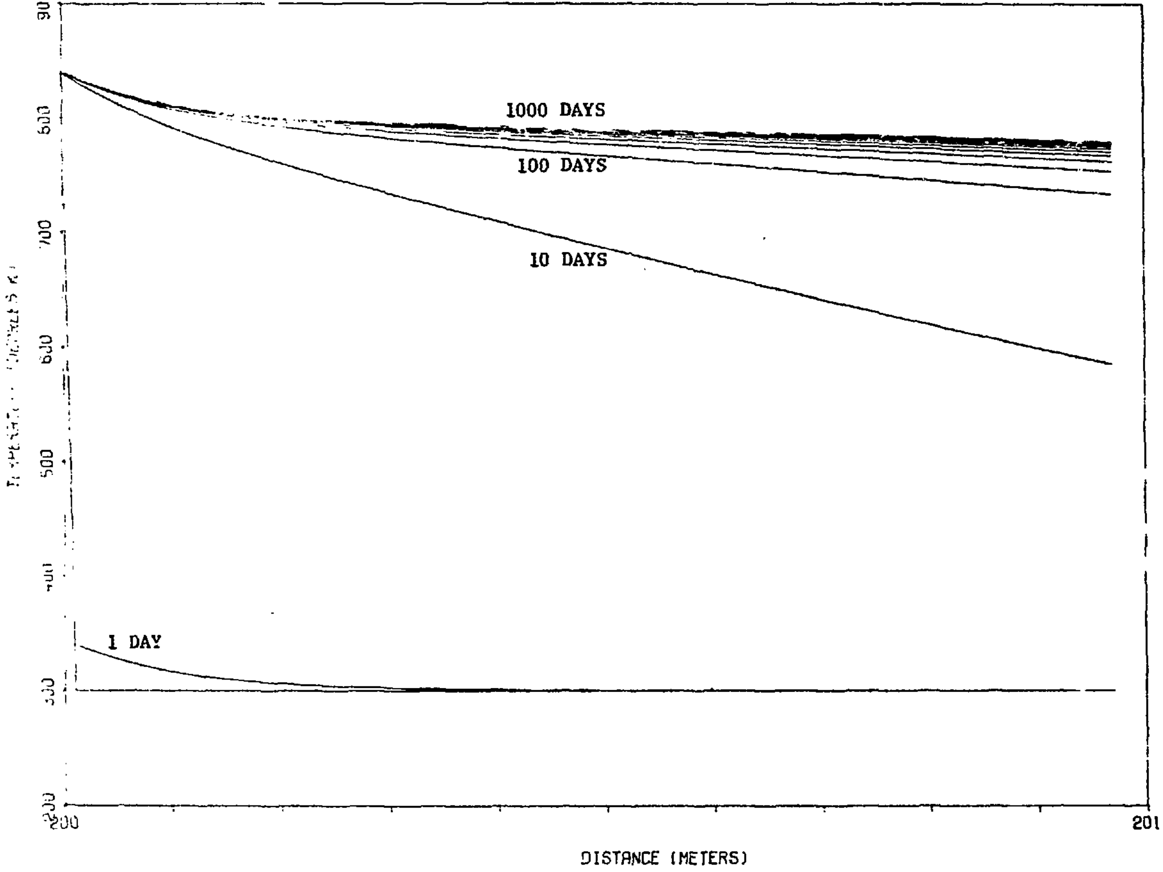


Fig. 3. HEATING OF A SALT CAVITY BY A DAILY 1 KT THERMAL PULSE ABSORBED IN 1.0 METERS. THE TEMPERATURE CURVES CORRESPOND TO 0,1,10,100,200,ETC.. PULSES.

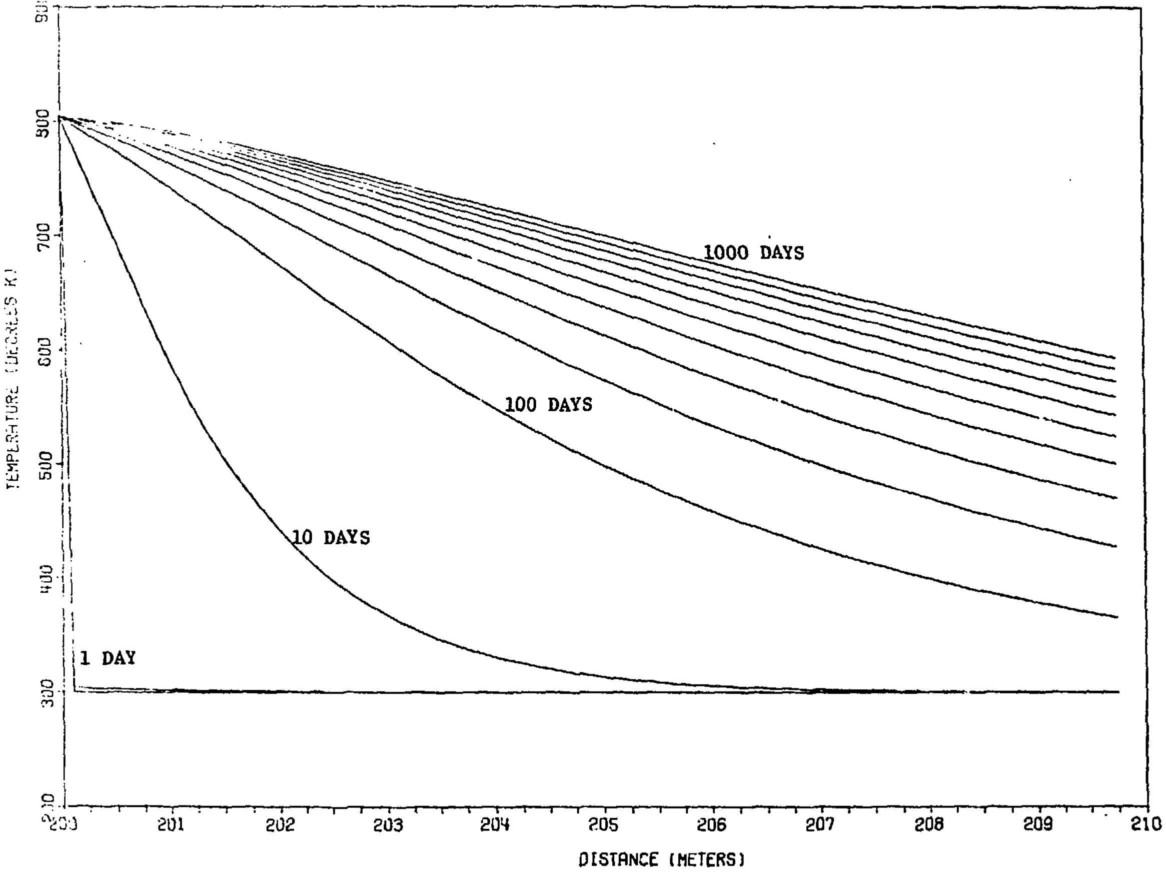


Fig. 4. HEATING OF A SALT CAVITY BY A DAILY 10 KT THERMAL PULSE ABSORBED IN .01 METERS. THE TEMPERATURE CURVES CORRESPOND TO 0.1.10.100.200.ETC.. PULSES.

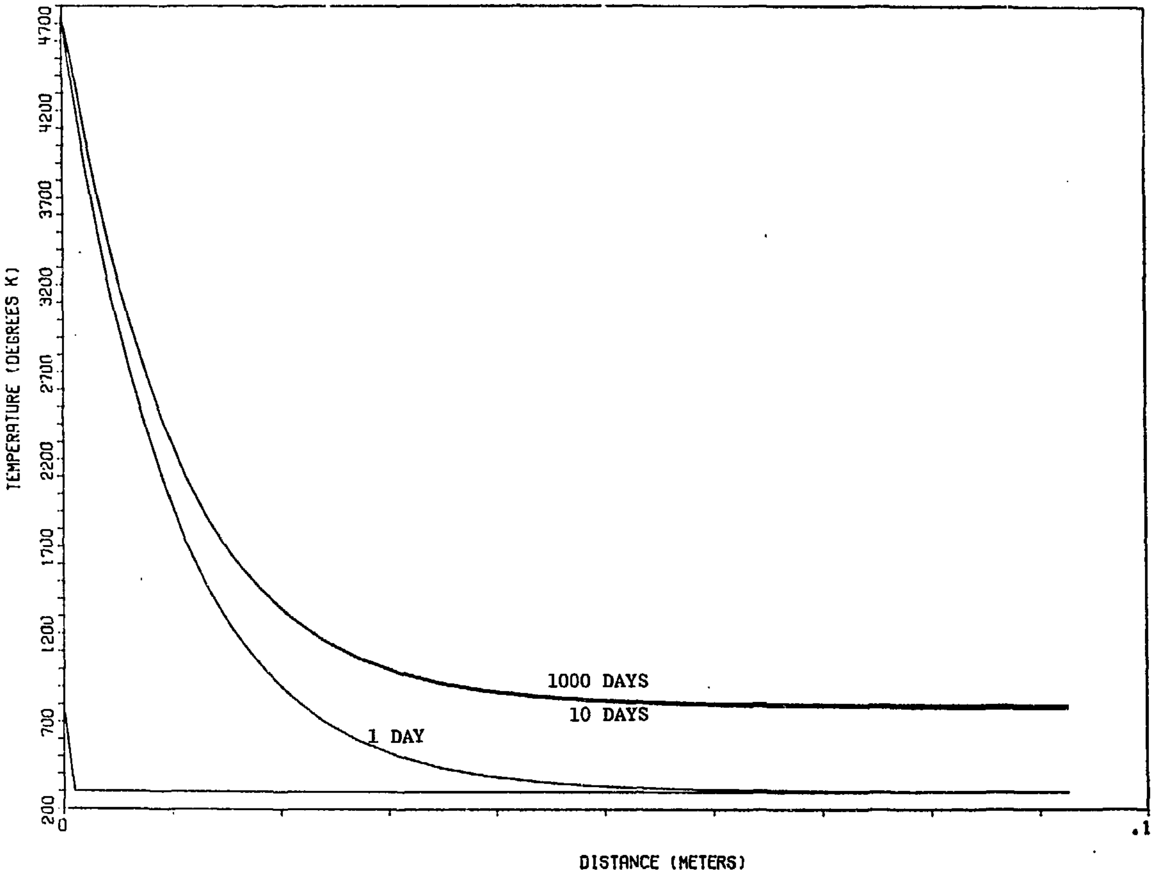


Fig. 5. HEATING OF A SALT CAVITY BY A DAILY 10 KT THERMAL PULSE ABSORBED IN 0.1 METERS.
THE TEMPERATURE CURVES CORRESPOND TO 0.1.10.100.200.ETC.. PULSES.

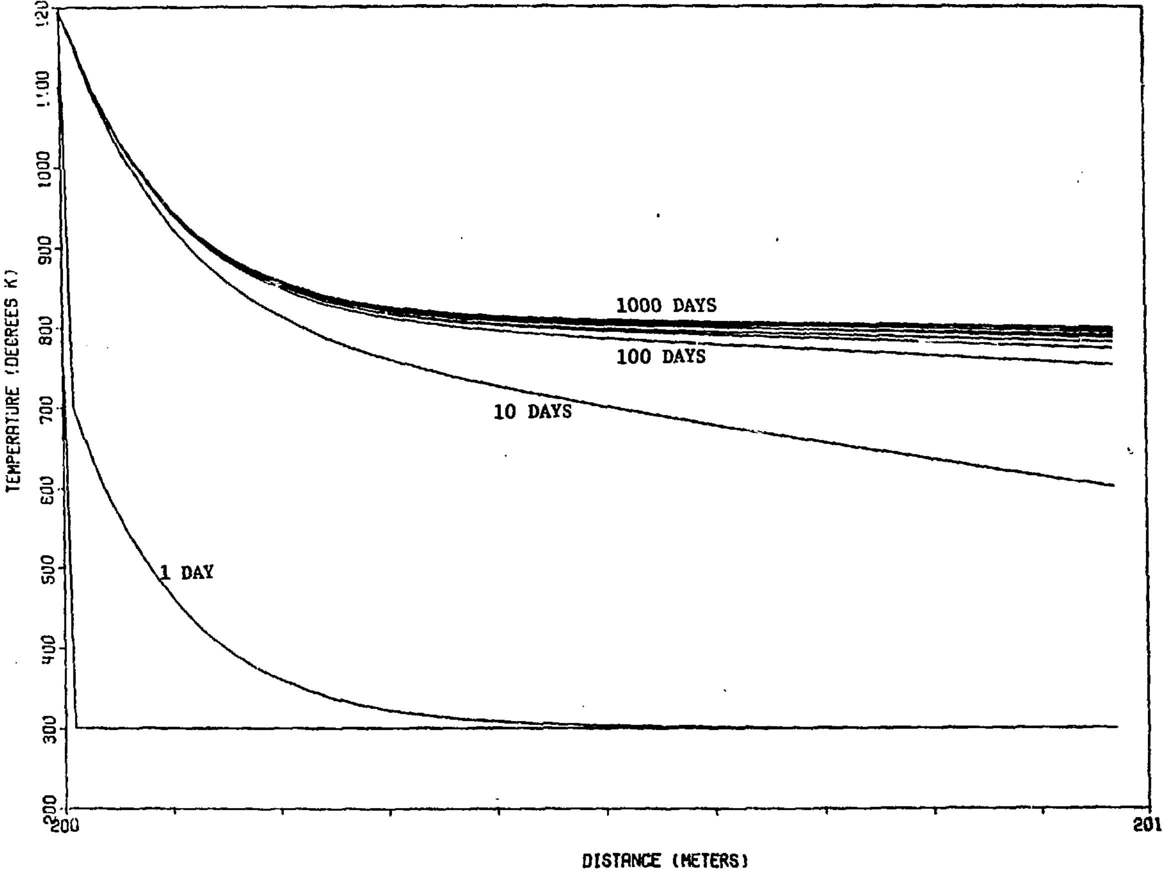
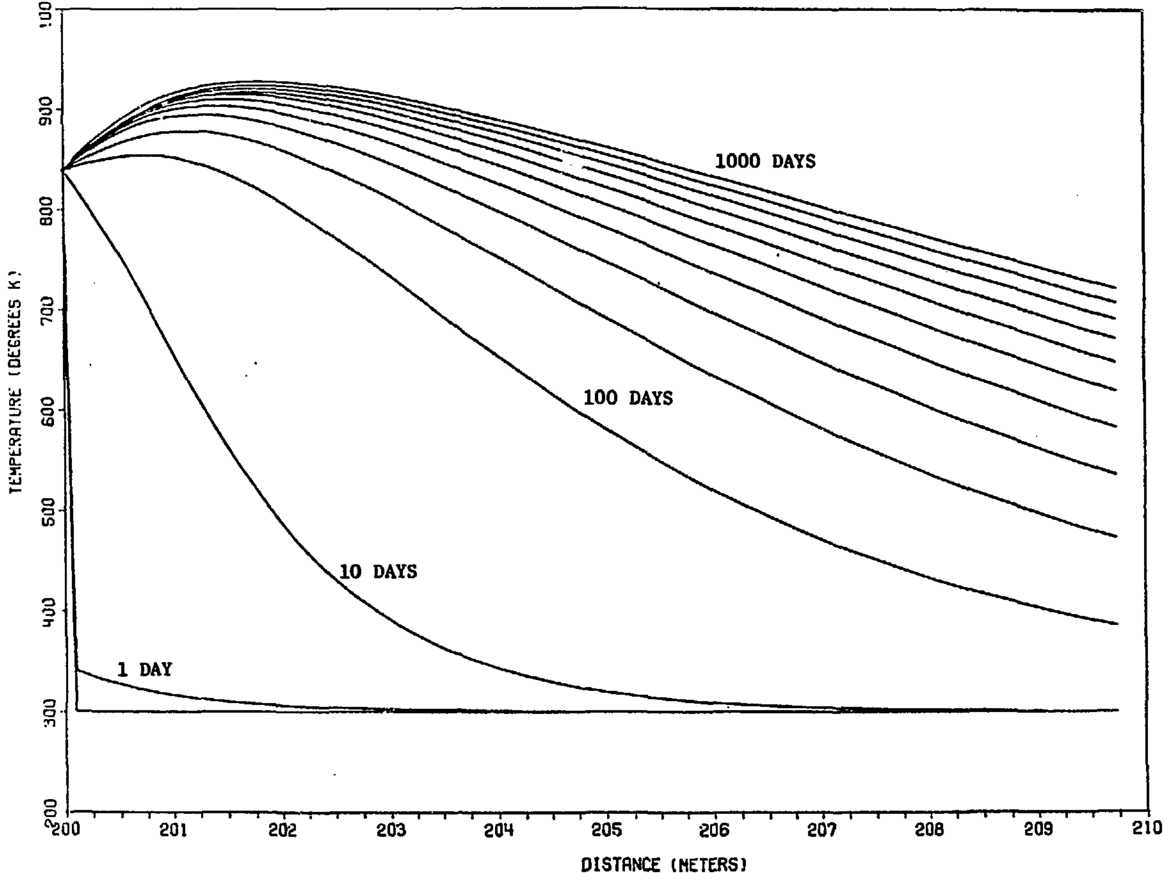


Fig. 6. HEATING OF A SALT CAVITY BY A DAILY 10 KT THERMAL PULSE ABSORBED IN 1.0 METERS. THE TEMPERATURE CURVES CORRESPOND TO 0.1.10.100.200.ETC.. PULSES.



A.12 RADIATION-HYDRO CALCULATION FOR PACER (R. McLean)

A.12.1 Introduction

A calculation using the HAROLD code to illustrate the effect of the wall-reflected shock on the fireball has been completed.

A.12.2 Initial Conditions

The initial configuration consisted of a 500 kg core of iron with a radius of one meter and containing 100 KT of energy shared between the radiation and thermal energy fields.

Surrounding this hot core out to a radius of 200 meters is .115 gm/cm^3 steam (.97 H_2O + .03 air + 7.2 x 10^{-5} NaCl) at 800°K. Initial velocities are zero.

These conditions result in a core density and pressure of .119 gm/cm^3 and 261 megabars respectively. The steam chamber contains 3.85 x 10^6 megagrams at a pressure of 294 bars. The initial energy in the steam amounts fo 805 KT or 89% of the total.

The first zone, representing the hot iron core, had an initial width of 1 meter while the remaining zones were determined by allowing successive zones to increase in mass by 10% out to about 46 meters whereupon the zone widths were held constant at 1.5 meters out to the wall radius of 200 meters. In all, 200 zones were used at the start. Later the problem was reduced to 93 zones.

A.12.3 Equations of State

1. Iron Core

For specific volume, $v\left[\frac{m^3}{\text{megagram}}\right]$ and temperature, $T\left[10^{4\,o}K\right]$, the pressure and internal energy are given as follows:

Pressure

$$v > .1273885 \rightarrow P = P_o$$

$$v \le .1273885 \rightarrow P = P_o + \frac{.6}{v^3} - \frac{13.4}{v^2} + \frac{122.8}{v} - 428.5$$

$$\text{where } P_o = 1.67457\,\frac{T^{3/2}}{v}$$

Energy

$$v \le .1335 \rightarrow E = E_o + 40000(.1335 - v)^4/v$$

$$.1335 < v \le .4 \rightarrow E = E_o + 1104(v - .1335)^4$$

$$.4 < v \rightarrow E = E_o + 5.56875$$

$$\text{where } E_o = 4.716\,v^{1/4}T^{3/2}$$

For these expressions, pressure is in $\left[\frac{\text{jerks}}{m^3}\right]$ while the energy is in $\left[\frac{\text{jerks}}{\text{megagram}}\right]$.

2. Steam

The steam was represented by $97\,H_2O + .03$ air $+ 7.2 \times 10^{-5}$ [illegible]

Values of $\frac{Pv}{RT}$ and $\frac{E}{RT}$, defined on the domain

$$\log_{10} T(^oK) = 2.8(0.1)7.2$$

by $\log_{10}\rho\left(\frac{gm}{cm^3}\right) = -4.5(0.5)0.5$,

were computed by Bob Lindgren and entered in the HAROLD code in tabular form. Plots (Figures 1 and 2) for each of these quantities ($\frac{Pv}{RT}$ & $\frac{E}{RT}$) are included for reference. Each curve corresponds to a different density as follows.

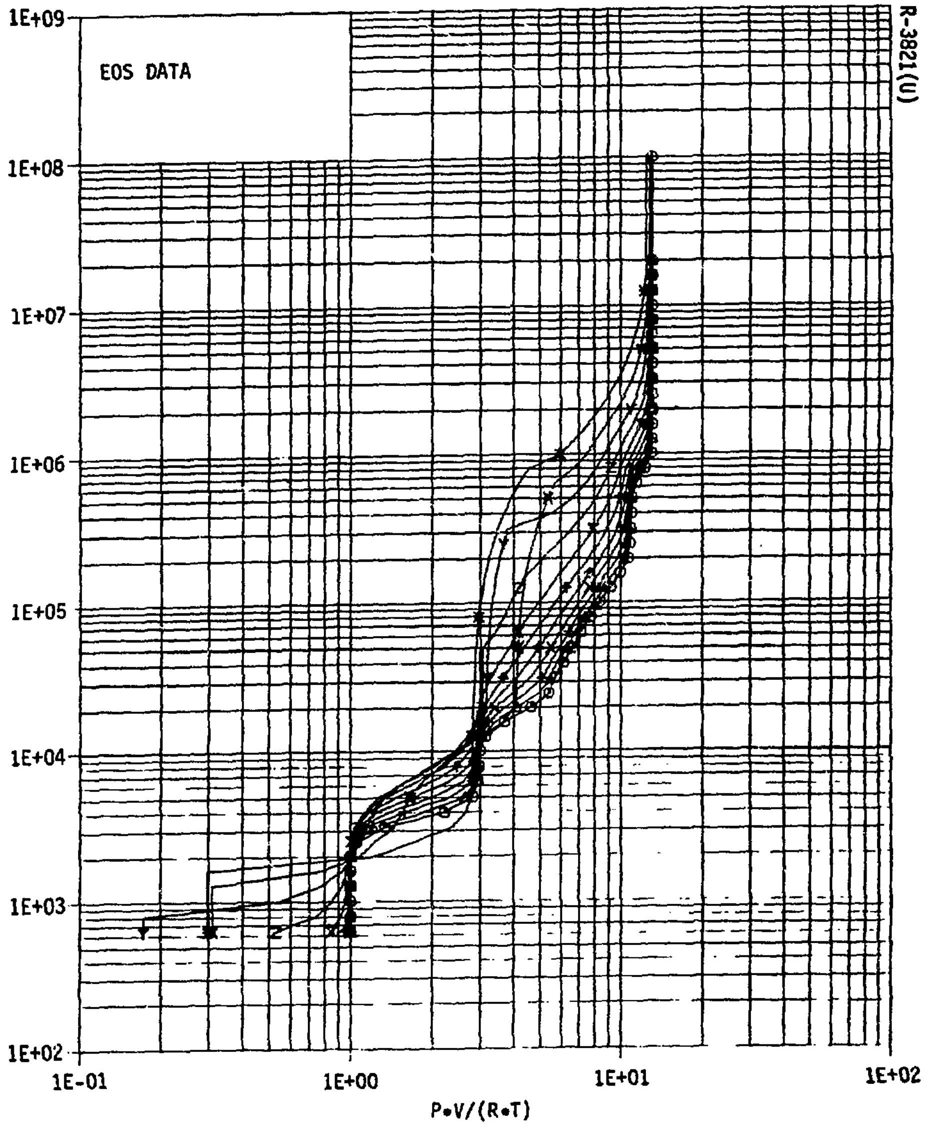
R-3821(U)
EOS DATA
1E+09
1E+08
1E+07
1E+06
1E+05
1E+04
1E+03
1E+02
1E-01
1E+00
1E+01
1E+02
P•V/(R•T)

Figure 1

A-91

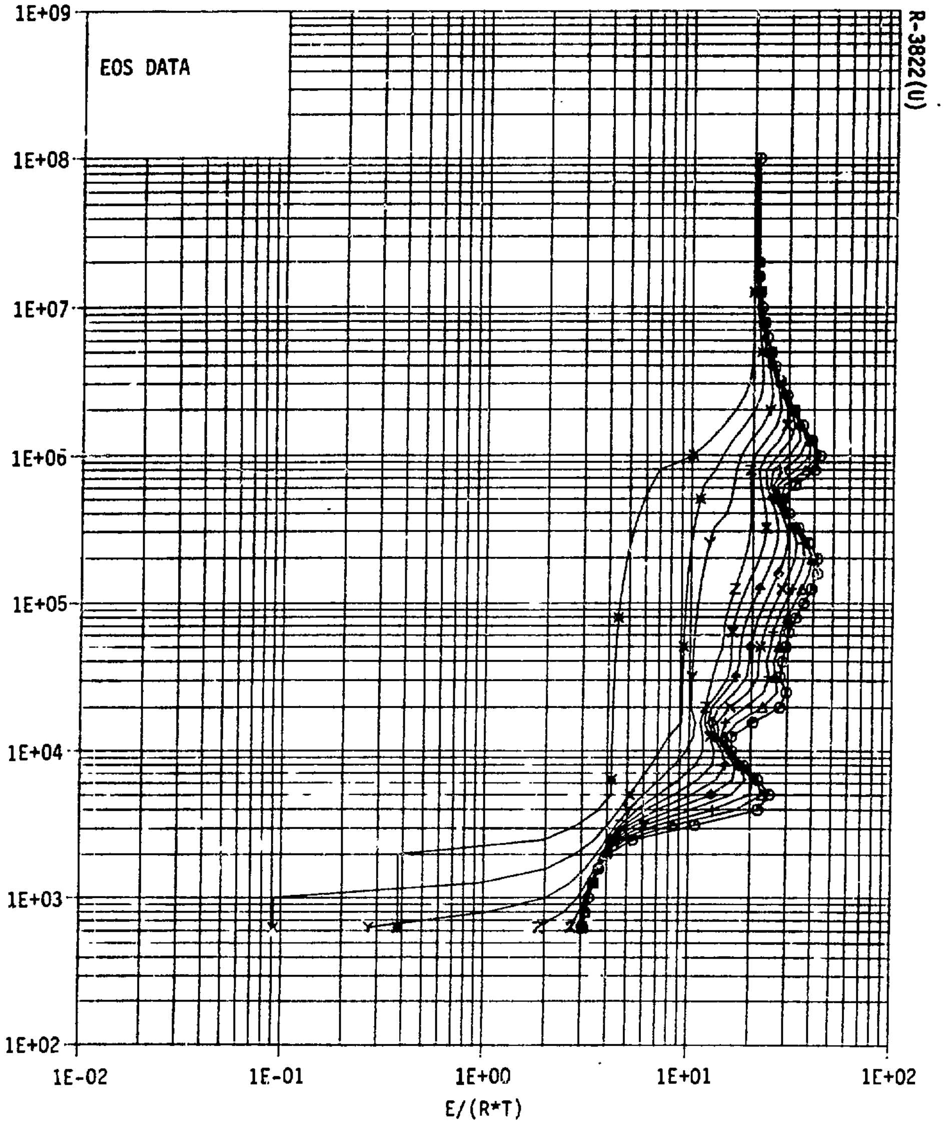

EOS DATA
R-3822(U)
1E+09
1E+08
1E+07
1E+06
1E+05
1E+04
1E+03
1E+02
1E-02
1E-01
1E+00
1E+01
1E+02
E/(R*T)

Figure [illegible]

[illegible]

$\log_{10}\rho$	curve symbol
-4.5	⬡
-4.0	△
-3.5	+
-3.0	×
-2.5	◇
-2.0	↑
-1.5	⧗
-1.0	Z
-0.5	Y
0.0	⌑
0.5	✱

For points (ρ, T) outside the domain of the table, the functions $\frac{Pv}{RT}$ and $\frac{E}{RT}$ are assumed to be constant at the value attained at the nearest boundary point of the table's domain.

A.12.4 Opacities

Opacities for both the iron and steam regions were represented by analytic fits; furthermore, the steam opacity was, in fact, an air opacity. The following expressions are for

$$\frac{3\kappa}{ac}$$

where κ is the opacity in m^2/megagram,

c = the velocity of light

and a = radiation density constant.

In Brode units,

$$\frac{3}{ac} = 1321 \left[\frac{\text{millisecs} - \text{m}^2 - (10^{4\,o}\text{K})^4}{\text{jerk}}\right]$$

T and v are temperature $\left[10^{4\,o}\text{K}\right]$ and specific volume $\left[\text{m}^3/\text{megagram}\right]$ respectively.

Iron Core

$$\frac{3\kappa}{ac} = 132000(.175 + .072d^{3/4}) \left[\frac{\text{m}^4 - \text{ms} - (10^{4\,o}\text{K})^4}{\text{megagram-jerk}}\right]$$

where $d = (\psi + \varepsilon)/v$

$$\psi = -97.806631 + .16146961T - .7421948 \times 10^{-4}T^2 + .13426503 \times 10^{-7}T^3 - .8495223 \times 10^{-12}T^4$$

$$\varepsilon = \text{EXP}(12.334948 - 7.0803 \times 10^{-3}T)$$

Steam (Air)

Let: $\eta = 773.395/v$

$$A = \frac{\frac{1}{\eta}\left(\frac{.912}{2.5 + .51\eta} + \frac{5.3 \times 10^{-5}}{\eta^2}\right)}{\left(\frac{.01075}{\eta}\right)\left(\frac{1}{1 + .025\eta}\right) + \frac{1.995 \times 10^{-6}}{\eta^3} + \frac{10^{-6}}{T^8}\left(\frac{.7767}{\eta} + \frac{3.933}{\eta^2} + \frac{1.3}{\eta^3}\right) + T^8}$$

$$F = .01\left(\frac{T^6}{1 + T^8}\right)\eta^{-3/2}$$

$$G = .0003\left(\frac{T^6}{2 + T^6}\right)\eta^{-1.82}$$

$$H = \left(\frac{1 + 1.16 \times 10^{-9}\eta^{\chi}T^4}{1 + 1.65 \times 10^{-8}\eta^{\chi}T^4}\right)\left(\frac{2.2 \times 10^{-8}\eta^{-1.72}T^4}{1 + 3.82 \times 10^{-11}\eta^{-.72}T^4}\right)$$

where $\eta > 1 \rightarrow \chi = .3$

$\eta \leq 1 \rightarrow \chi = -.3$

Then,

$$\frac{3\kappa}{ac} = 1321.2\ \frac{v}{\overline{\lambda}} \left[\frac{m^4 - ms - (10^{4}\,{}^{\circ}K)^4}{\text{megagram-jerk}}\right]$$

where $\overline{\lambda} = A + F + G + H.$

A plot (Fig. 3) of this latter opacity is included with a curve for each of the densities used in the EOS table for steam. The same curve symbol notation also applies.

A.12.5 Grey Body Radiation Loss

A radiation loss term was included for the material in the steam within one emission mean free path of the salt wall. It is computed as follows:

$$L_j = \sigma R_j^{\,2} T_j^{\,4}\left(\frac{\Delta t}{\Delta m_j}\right)\left(\frac{\Delta R_j}{\lambda_j}\right)$$

where

$\sigma = 5.67 \times 10^{-4}\left[\frac{\text{jerks}}{m^2 - ms - (10^{4}\,{}^{\circ}K)^4}\right]$

R_j = radius at center of jth zone [meters]

ΔR_j = width of jth zone [meters]

Δm_j = mass of jth zone [megagrams]

Δt = time step [ms]

T_j = temperature of jth zone [$10^{4}\,{}^{\circ}K$]

λ_j = emission mean free path in jth zone (meters).

D_j has units of [jerks/megagram] and is the energy/unit mass lost from the jth zone in Δt ms. This loss occurs only in those zones (or parts thereof) within one mean-free path of the wall. A further correction factor is applied to this loss to account for the cold air transmission

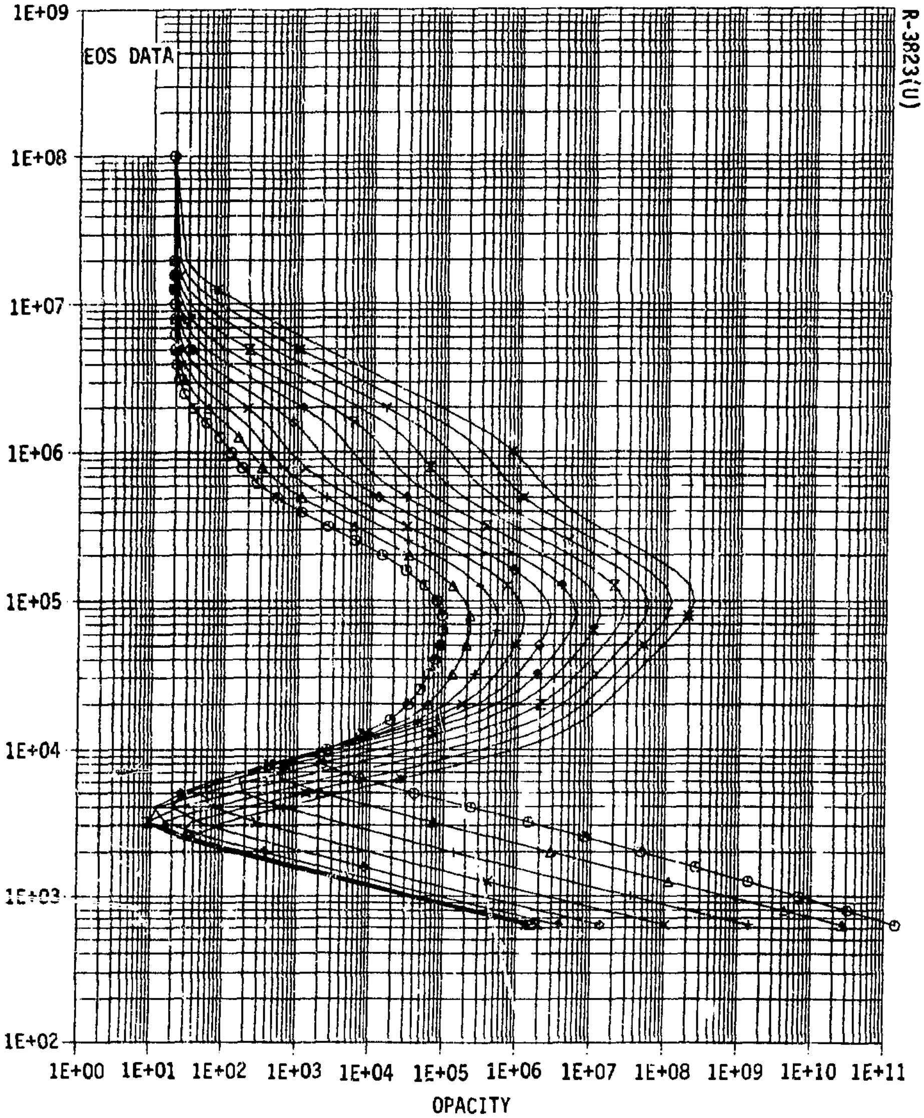

EOS DATA
R-3823(U)
1E+09
1E+08
1E+07
1E+06
1E+05
1E+04
1E+03
1E+02
1E+00
1E+01
1E+02
1E+03
1E+04
1E+05
1E+06
1E+07
1E+08
1E+09
1E+10
1E+11
OPACITY

Figure 3

cutoff in the ultraviolet region. The loss becomes, finally,

$$\left(\frac{25}{25 + 3.5T^2 + T^3}\right)D_j$$

where T is again in (10^4°K). It is important to remember that the λ_j used was for air and not steam.

A.12.6 Results

The purpose for running this problem was to observe the effect on the fireball of the wall reflected shock and its subsequent reverberations. The hope is that the fireball edge will experience sufficient accelerations to help break the fireball up before it reaches the dome ceiling. This rise time has been estimated to be about 10 to 15 seconds. Also of some interest was the pressure history on the wall itself.

The wall receives the shock at about 211 ms and experiences an overpressure of 206 bars at 920°K. At about 445 ms the fireball reaches maximum compression from the wall reflected shock. Figures 4 and 5 are temperature and density plots for these times. Figure 6 gives the velocity history, $\dot{R}$, for a zone in the fireball-steam interface corresponding to a point at about 50 meters on the 445 ms curve in Figure 4. Figure 7 is a time history of the overpressure, ΔP, at the salt dome wall. Figure 8 is a blow-up of Figure 7 in a time neighborhood of the time at which the shock first hits the wall. Finally, Figure 9 gives peak pressure, P, in the shock versus radius as the primary shock makes its initial passage out to the wall.

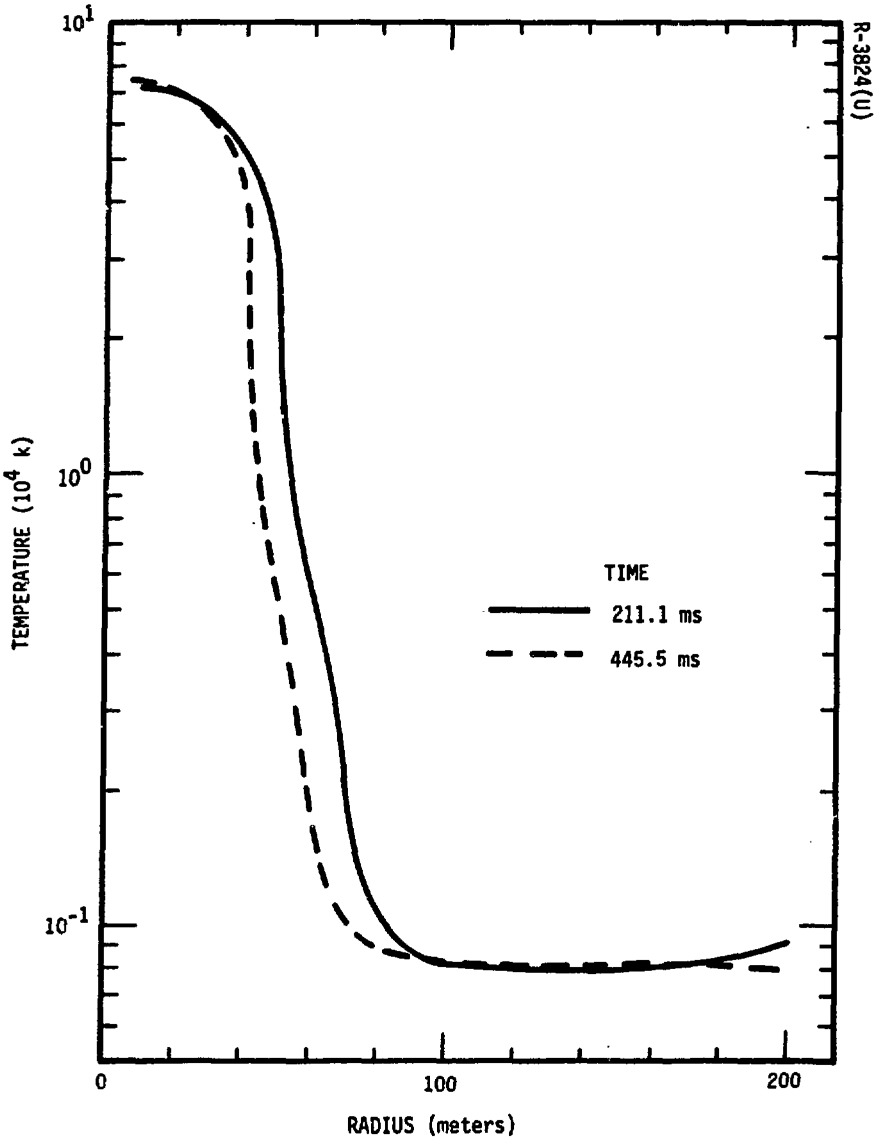

10^1
10^0
10^{-1}
TEMPERATURE (10^4 k)
0
100
200
RADIUS (meters)
TIME
211.1 ms
445.5 ms
R-3824(U)

Figure 4

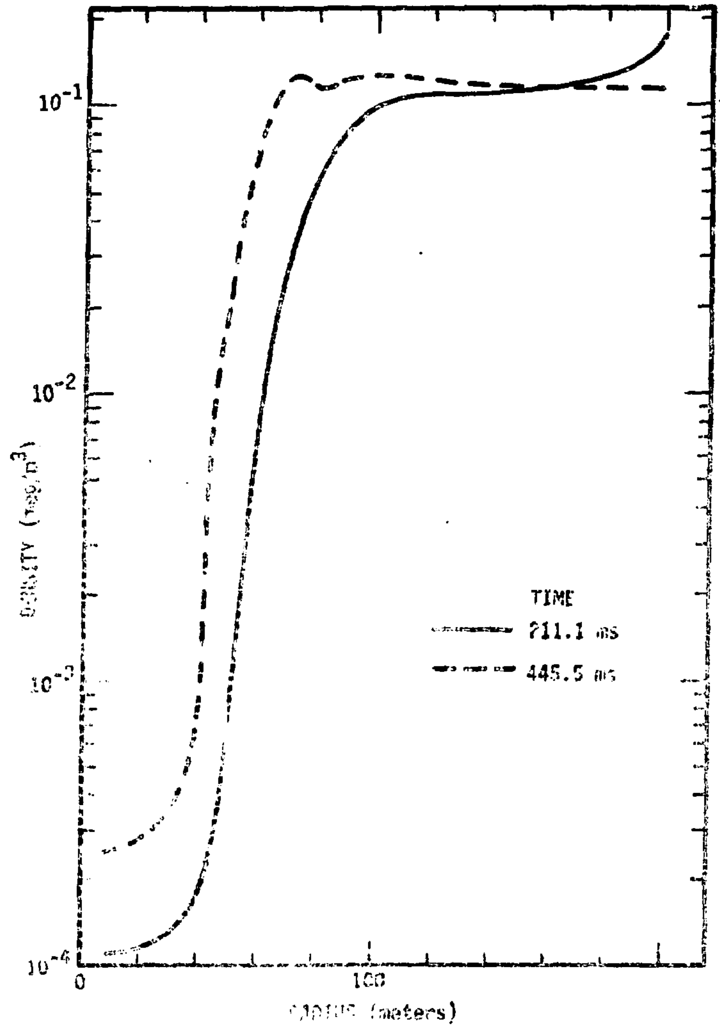

10^-1
10^-2
10^-3
10^-4
DENSITY (kg/m^3)
0
100
RADIUS (meters)
TIME
211.1 ms
445.5 ms

Figure 5

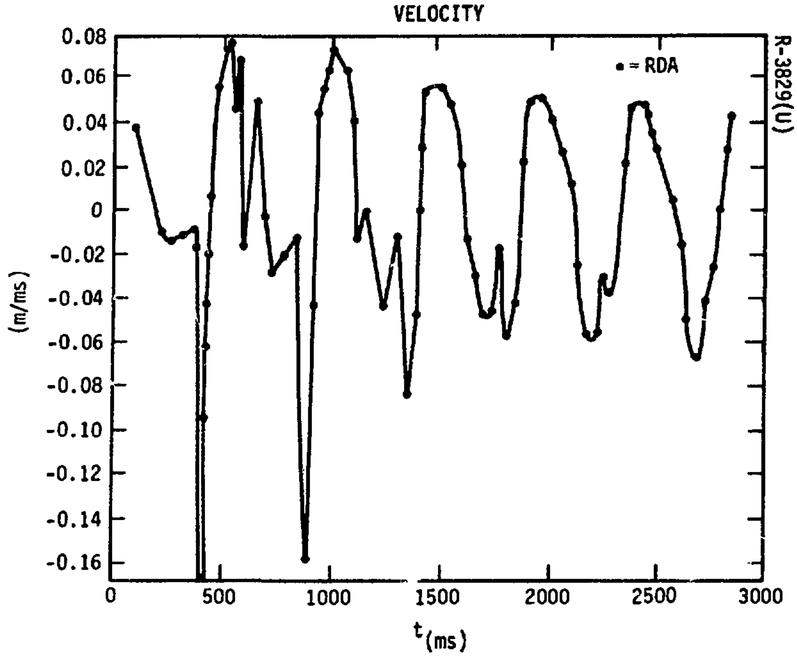

VELOCITY
● = RDA
R-3829(U)
(m/ms)
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.10
-0.12
-0.14
-0.16
0
500
1000
1500
2000
2500
3000
$t_{(ms)}$

Figure 6

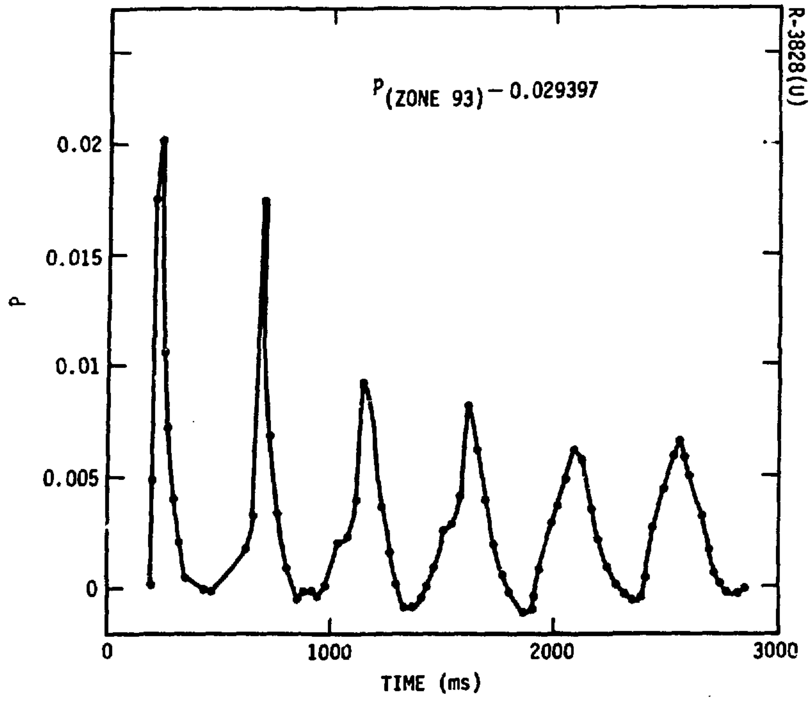

P(ZONE 93) − 0.029397
R-3828(U)
P
0.02
0.015
0.01
0.005
0
0
1000
2000
3000
TIME (ms)

Figure 7

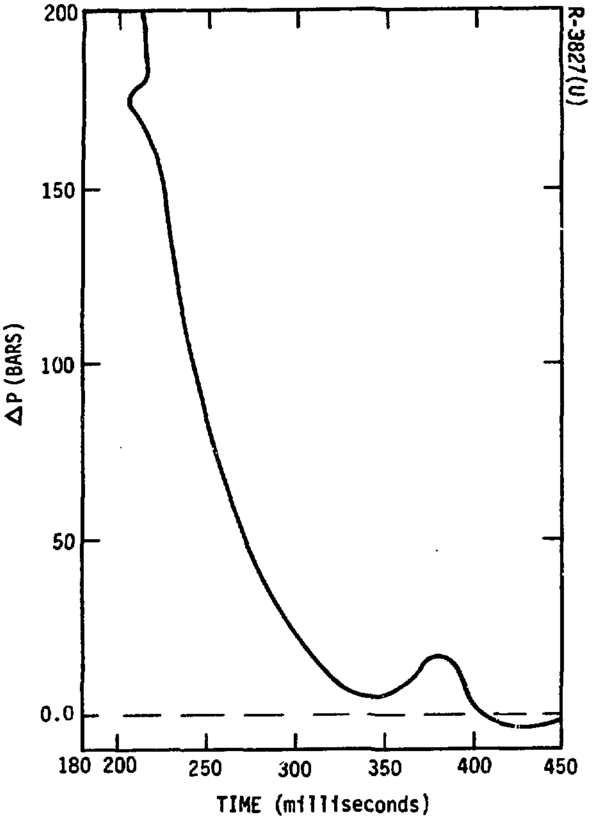

R-3827(U)
ΔP (BARS)
200
150
100
50
0.0
180
200
250
300
350
400
450
TIME (milliseconds)

Figure 8

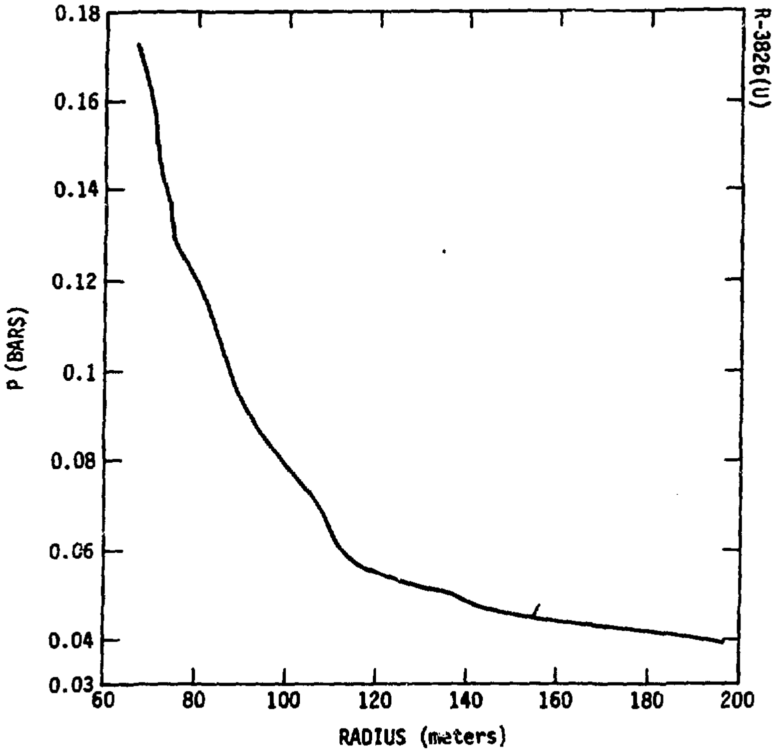

0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.03
P (BARS)
60
80
100
120
140
160
180
200
RADIUS (meters)
R-3826(U)

Figure 9

A.13 RAYLEIGH-TAYLOR INSTABILITY IN A FLUID WITH VARIABLE DENSITY

(M. Plesset)

We consider the following problem: for $z < o$, we have a fluid of density ρ_1; for $z > d$ the fluid has density ρ_2; and for $o \leq z \leq d$, the density is $\rho = \rho_1 e^{\beta z}$ so that $\rho_2 = \rho_1 e^{\beta d}$. We suppose also that the unperturbed pressure field gives a constant acceleration g in the -z direction. This problem has been considered by Rayleigh* in the so-called Boussinesq approximation; that is, while density variations may be large, compressibility effects are small. The problem is a stability problem, and as is usual it is treated by linearization. It may be remarked that the elementary instability case is the one in which the density change is a step-function of z, say. It might very well be expected that the situation in which the density changes over a finite distance would occur quite often. The only such case which has been successfully treated is the one in which the density transition is given by an exponential function.

The solution of the problem is straightforward and the procedure may be given here since it can be formulated and solved in a rather brief way. While the density varies, the particle density is supposed not to change in accord with our assumption of incompressibility. Thus

$$\frac{D\rho}{Dt} = \frac{\partial \rho}{\partial t} + u \frac{\partial \rho}{\partial x} + w \frac{\partial \rho}{\partial z} = o \qquad (1)$$

where we are making the "plane-assumption" that in the direction perpendicular to g the field quantities vary only with x. The velocity in the x-direction is u and in the z-direction it is w. The equation of continuity is

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u) + \frac{\partial}{\partial z}(\rho w) = o, \qquad (2)$$

which because of Eq. (1) gives

$$\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = o. \qquad (3)$$

The velocities u, w are supposed to be small quantities in accordance with the perturbation approach. The pressure is $p^* = p + p'$, and the density

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*Rayleigh, Proc. Lond. Math. Soc. vol. 14, pp. 170-177 (1883).

is $\rho^* = \rho + \rho'$ where p is the unperturbed pressure, and p' is a small quantity. The density ρ is the unperturbed density with a dependence only on z as described above and ρ' is a small quantity. The equations of motion in the x- and z-directions

$$\left.\begin{aligned} \rho^* \frac{\partial u}{\partial t} &= - \frac{\partial p^*}{\partial x}, \\ \rho^* \frac{\partial w}{\partial t} &= - \frac{\partial p^*}{\partial z} - g\rho^* \end{aligned}\right\} \qquad (4)$$

in the linearized approximation become

$$\rho \frac{\partial u}{\partial t} = - \frac{\partial p'}{\partial x} \qquad (5)$$

$$\rho \frac{\partial w}{\partial t} = - \frac{\partial p'}{\partial x} - g\rho'. \qquad (6)$$

Equation (1) may be written

$$\frac{\partial \rho'}{\partial t} + w \frac{\partial \rho}{\partial z} = o . \qquad (1')$$

We now take the x and t dependence of ρ', p', u, w to be of the form $e^{nt + ikx}$ so that Eqs. (1'), (3), (5), and (6) give

$$n\rho' + w \frac{d\rho}{dz} = o; \qquad (7)$$

$$iku + w_z = o; \qquad (8)$$

$$n\rho u + ikp' = o; \qquad (9)$$

$$n\rho w + p'_z + g\rho' = o. \qquad (10)$$

In these equations $w_z = dw/dz$, $p'_z = dp'/dz$, and ρ is a given function of z. These equations apply in the region $o \leq z \leq d$. The equation for w(z) in this region is easily obtained as follows. From Eqs. (8) and (9) one gets upon elimination of u

$$-p' = \frac{n\rho w_z}{k^2}.$$

From Eqs. 7) and (10) upon elimination of ρ' one gets

$$-p'_z = n\rho w - \frac{g}{n}\rho_z w.$$

The function p' may then be eliminated using these last two equations to get the equation for w:

$$w_{zz} + \beta w_z - wk^2(1 - \frac{g\beta}{n^2}) = o, \qquad o \leq z \leq d. \qquad (11)$$

The quantity β is ρ_z/ρ. In the regions $z < o$ and $z > d$ we have $\beta = o$ so that the vertical velocity w satisfies the equation

$$w_{zz} - k^2 w = o, \qquad (12)$$

in both of these regions.

It is a straightforward matter to find n as a function of k, g, and β. If m_1 and m_2 are the roots of

$$m^2 + \beta m - k^2(1 - \frac{g\beta}{n^2}) = o,$$

the solution for the region $o \leq z \leq d$ is

$$w = Ae^{m_1 z} + Be^{m_2 z}. \qquad (13)$$

In the region $z > d$, the appropriate velocity solution of Eq. (12) must behave like e^{-kz} since the disturbance must approach zero as $z \to +\infty$. It follows that we have

$$\frac{dw/dz}{w} = -k$$

as $z \to d$ from above. For continuity we must have for the solution in the inner region, as given by Eq. (13),

$$\frac{m_1 A e^{m_1 d} + m_2 B e^{m_2 d}}{A e^{m_1 d} + B e^{m_2 d}} = -k. \tag{14}$$

Similarly the velocity in region $z < o$ must behave like e^{kz} so that continuity of the solutions at $z = o$ requires

$$\frac{m_1 A + m_2 B}{A + B} = k. \tag{15}$$

Elimination of A and B from these two equations leads to the relation

$$(m_1 + k)(m_2 - k)\, e^{m_1 d} = (m_1 - k)(m_2 + k)\, e^{m_2 d} \tag{16}$$

which is readily put in the form

$$\frac{(m_2 - m_1)k}{m_1 m_2 - k^2} = \tanh \frac{(m_2 - m_1)d}{2}. \tag{17}$$

If one defines

$$\theta = (m_2 - m_1)d,$$

then Eqn. (17) may be written as

$$\frac{kd\theta}{(\beta^2 d^2/4) - k^2 d^2 - (\theta^2/4)} = \tanh \frac{\theta}{2}. \tag{18}$$

Equation (18) is a transcendental equation which determines θ. Then from the definition of θ:

$$\theta^2 = d^2(m_2 - m_1)^2 = \beta^2 d^2 + 4k^2 d^2 \left(1 - \frac{g\beta}{n^2}\right), \tag{19}$$

one finds n.

One can see how the solution behaves in the limiting case of a discontinuous jump in density by letting $d \rightarrow o$ while βd is kept finite. It is evident that θ then has the approximate value βd. If we use this approximate value on the right hand side of Eqn. (18), we can get an improved value as

$$\frac{1}{4}\beta^2 d^2 - \frac{1}{4}\theta^2 = kd\beta d \coth\frac{\beta d}{2},$$

and, if this value is used in Eqn. (19), one finds

$$n^2 = gk\,\frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}$$

so that one has the usual instability if $\rho_2 > \rho_1$.

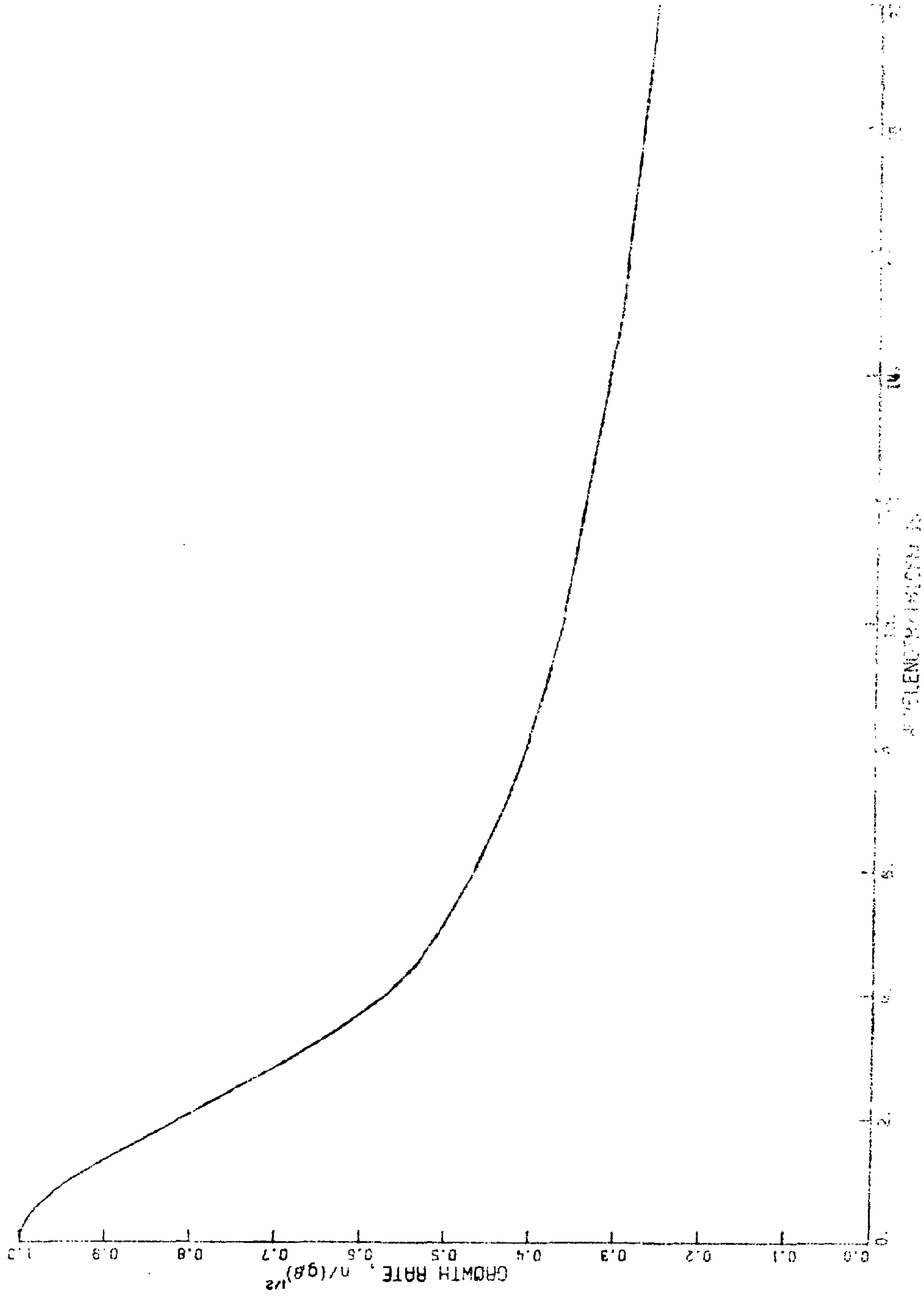
For the finite transition region, the practical approach appears to be to find the roots for θ of Eqn. (18) by a numerical method. Then given a solution for θ of this equation, the value of n is then determined from Eq. (19). One obvious root of Eqn. (18) is $\theta = o$ which gives

$$n^2 = \frac{4g\beta k^2}{\beta^2 + 4k^2} \tag{20}$$

which goes to zero as $k \rightarrow o$, and as $k \rightarrow \infty$, n approaches the value

$$n^2 = g\beta. \tag{21}$$

A numerical solution of Eqns. (18) and (19) is shown in the figure where the dependence of $n/(g\beta)^{\frac{1}{2}}$ on λ/d is shown for the case that $\beta d = 4.5$. This value of βd corresponds to a density ratio $\rho_2/\rho_1 = 90$.


GROWTH RATE, n/(gβ)^1/2
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
0
2

A.14 PACER FIREBALL INSTABILITY AND COOLING (H. Hubbard)

A.14.1 Introduction

One of the first problems noted in protecting the walls of the PACER cavity from the effects of the explosion is that the hot, low density fireball rises under gravity, and what is to prevent it from melting salt from the top of the cavity? Calculations by Jones [1] showed this expected behavior, and temperatures were estimated above 1100°K, the melting point of salt.

Another effect of the confined space of the explosion is the radial shock and subsequent motion of the fluid, causing the fireball to be compressed, expand, recompressed, etc. by a breathing mode on successive shock reverberations. As the cold gas behind the shock compresses the very low density fireball gas, the latter is decelerated, turned around and sent back. During the deceleration phase, the interface between the hot and cold materials is unstable, i.e., any perturbation of the interface will grow exponentially during this phase, resulting in fingers of cold gas remaining behind in the fireball. Because of the very large density difference, cooling will be efficient when this occurs.

A.14.2 Approximations of the Theory

To investigate this effect in a somewhat more quantitative way, a rad-hydro problem was run [2] and accelerations of the fireball interface during its oscillation were computed. (The interface velocity is shown in Figure 6 of Section A.12 of this appendix.) The standard Rayleigh-Taylor theory of the instability [3] growth $e^{\alpha t}$ gives

$$\alpha^2 = \frac{2\pi g}{\lambda}\left(\frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}\right) \qquad (1)$$

where $g = \ddot{R}$ in one problem is the acceleration, λ is the wavelength of the disturbance, and ρ_1 and ρ_2 are the light and heavy densities. This simple theory applies to a plane interface with a density discontinuity, incompressible flow, and constant acceleration. None of these conditions is met precisely: the assumption of incompressible flow is not serious during the moments of deceleration, nor is the plane approximation since we are not interested in gross asphericities. The effect of including a gradual change from low to high density at the bubble edge has been taken into account by M. Plesset in Section A.13 of this Appendix and it modifies the Taylor result somewhat:

$$\alpha^2 = \beta g \, f^2 \left(\frac{\lambda}{d}\right) \qquad (2)$$

where $\frac{\rho_2}{\rho_1} = e^{\beta d}$, d is the thickness of transition layer and f(x) has a maximum of 1 at $\lambda = 0$ and falls off like a bell-shaped curve (given in M. Plesset's section of this Appendix).

It has been assumed that the theory for constant acceleration can be applied, using average acceleration; i.e., we compute

$$\int \alpha dt = f\sqrt{\beta}\int\sqrt{\ddot{R}}dt$$

over the period of $\ddot{R} > 0$, and assume the result is the same as $\bar{\alpha}\Delta t$ for constant α.

A.14.3 Application to PACER

The breathing motion of the fireball in the Harold calculation is ∿ 1/4 of the radius of ∿55 m average. Assuming that a perturbation of wavelength λ starts at amplitude $K\lambda$ and must grow to δR for good mixing, the condition is

$$KAe^{\lambda dt} \quad \delta\pi$$

or

$$K \approx \frac{5.56}{\lambda/d} \exp\left\{ f(\lambda/d)\sqrt{\beta} \int \sqrt{\ddot{R}}\, dt \right\} \tag{3}$$

The computation from the results of McLean's calculation (Section A.12) yield the following data for the integral during the successive unstable phase:

t_1, t_2 (ms)	$\int_{t_2}^{t_1} \sqrt{\ddot{R}}\, dt$ (meters $^{1/2}$)
407.2, 537	6.35
884, 997	3.95
1333, 1448	3.57
1818, 1942	3.19

Taking $\delta = \pi/4$, $d = 10$m, $\beta = 0.45\text{m}^{-1}$ and using results from the first pulse only ($6.35\text{m}^{1/2}$) an application of (3) yields the minimum amplitude for good mixing as a function of disturbance wavelength

λ (meters)	1	2.5	5	10	20
Min. amplitude (meters)	0.2	0.2	0.21	0.2[illegible]	[illegible]

A perturbation as large as 20 cm will, therefore, be likely to cause good mixing from the first shock. The result of successive compressions will greatly enhance the mixing. The reverberation time of the shock is ~1/2 sec so there are many oscillations possible before the fireball rises too far. (The time to reach the top of the cavity is ~12 sec according to Jones' calculation [1].) If one repeats the calculation for the integrated effect of the first four reverberations listed above, the results are as follows:

λ (meters)	1	2.5	5	10	20
Min. amplitude (meters)	$2.9\text{x}10^{-5}$	$8.3\text{x}10^{-5}$	$1.9\text{x}10^{-4}$	$5.5\text{x}10^{-4}$	$2.9\text{x}10^{-3}$

Obviously, if the cummulative effect of successive shocks is additive as assumed here, then essentially all available material will mix.

The maximum mixing that can occur by this mechanism is given by the fraction of the fireball volume engulfed on compression, $1-(1-\delta)^3$, times the density ratio, which is ~600. For $\delta = 1/4$, the ratio of mass mixed to that of the fireball is

$$\frac{m}{m_o} = \frac{\rho_2}{\rho_1}\left[1-(1-\delta)^3\right] = 600 \times .578 \approx 350.$$

If all this material mixed, the final fireball temperature T, would be given by

$$(m+m_o)T = m\,T_{amb} + m_o T_o$$

or

$$T \approx T_{amb} + \frac{m_o}{m}\,T_o$$

where $T_{amb} \cong 800°K$ is the ambient temperature and $T_o \approx 3.5 \times 10^4 °K$ is the initial fireball temperature. These values yield $T \approx 900°K$, and the density would be 60% of ambient. Probably turbulent mixing would follow and produce further equilibration.

Clearly such a complex process can only be roughly estimated by these methods, but they do indicate a high probability of fireball cooling in a natural way.

REFERENCES

1. E. M. Jones, PACER Program--A Strong Explosion in a Spherical Cavity: Two-Dimensional Evolution, Los Alamos Scientific Laboratory, LA-5427-MS, October 1973.
2. G. Taylor, The Instability of Liquid Surfaces When Accelerated in a Direction Perpendicular to their Planes. I, Proc. Royal Soc. London, Vol. 201A, No. 1065, March 22, 1950.

APPENDIX B. PROJECT 3--ENGINEERING

B.1 THROTTLED STEAM FOR POWER GENERATION (L. Gore)

B.1.1 Introduction

The proposed operating conditions in the salt dome cavity are 440 bars and 500 to 600°C, or 6400 lb/in^2 and 900 to 1100°F. This pressure is much higher than the pressure used for most steam power equipment and presents a difficult problem in equipment design.

One method for overcoming this difficulty is to throttle the steam coming from the cavity to a pressure of about 2500 lb/in^2. At this pressure more or less conventional equipment can be used such as the steam generators developed for pressurized water reactor systems.

After removal of heat from the cavity steam it can be returned to the cavity as a liquid in order to minimize the returned fluid pumping power.

B.1.2 Objective

The object of this report is to examine the concept of throttling as it affects the power generating system.

B.1.3 Conclusions

For a 2000 MW(e) plant and throttling to 2500 lb/in^2 the power required for pumping the returned liquid is about 100 MW, depending upon the temperature of the returned liquid. This represents 5 percent of the plant output.

The large pressure drop associated with throttling to 2500 lb/in^2 can be used to overcome fluid flow friction in the 2 km (6500 ft) long supply pipe. As a result, a pipe diameter of 2 to 3 ft is adequate.

B.1.4 Analysis

Figure 1 illustrates the operation of a throttled 2500 lb/in^2 plant. Steam from the cavity at 6400 lb/in^2 and 1000°F arrives at the surface at 2500 lb/in^2 and 810°F, the reduction in temperature being a Joule-Thomson effect. In the pressurized water system the steam is mixed with water in the circulating water loop where it heats the water from 550°F to 650°F. The hot water passes through a heat exchanger or boiler where it generates steam for the turbine at about 500°F and 680 lb/in^2.

The injection pump returns 550°F liquid to the cavity at a rate equal to the steam usage rate.

The enthalpy of the cavity steam is 1310 Btu/lb, that of the 550°F returned liquid is 550 and the heat used is 860 Btu/lb. Assuming a 2000 MW(e) plant with a 30 percent thermal efficiency, 6700 MW thermal is required. The corresponding steam mass flow rate is $6700 \times 10^3 \times 3415/760 = 30.0 \times 10^6$ lb/h. The specific volume of the steam in the cavity is .093 ft^3/lb and .234 ft^3/lb at the top (10.75 and 4.28 lb/ft^3, respectively). Thus, the weight of the vertical column of steam is about 350 lb/in^2 and the pressure difference available to overcome friction in the pipe is

$$6400 - 2500 - 350 = 3550 \text{ lb/in}^2$$

If a 2 ft diameter pipe is assumed, the mass flow rate per unit area is

$$G = 30.0 \times 10^6/(3.14 \times 3600) = 2650 \text{ lb/ft}^2\text{sec}$$

Using a value of .075 lb/h-ft for the viscosity, the Reynolds number for the flow in the pipe is

$$2650 \times 3600 \times 2/.075 = 2.5 \times 10^8$$

and the corresponding friction factor f for a rough pipe is about .003. The number of dynamic velocity heads lost in friction will be

$$4f\ L/D = 4 \times .003 \times 6560/2 = 40$$

where L is pipe length and D diameter. Using q for the dyanmic pressure

$$q = 3550/40 = 88.5\ \text{lb/in}^2$$
$$q = \bar{v}\ G^2/(2g)$$

where $\bar{v}$ is the average specific volume and g is the gravitational constant. Solving for G

$$G^2 = 88.5 \times 144 \times 2 \times 32.2/.163 = 5.03 \times 10^6$$
$$G = 2250\ \text{lb/ft}^2\text{sec}$$

The velocity in the pipe is

$$V = G\ \bar{v} = 2250 \times .163 = 365\ \text{ft/sec}$$

and the area of the pipe cross section is

$$A = 30.0 \times 10^6/(2250 \times 3600) = 3.70\ \text{ft}^2$$
$$D = 2.17\ \text{ft}$$

The change in the friction factor f corresponding to this diameter will not significantly alter the calculations.

Considering the pumping of the returned liquid, the specific volume at 550°F is about .0218 ft^3/lb and the weight of the liquid column is 2100 lb/in^2.

The viscosity of the liquid is about .20 lb/h-ft and if the diameter of the return pipe is the same as the diameter of the steam pipe, the Reynolds number for the flow will be

$$2250 \times 3600 \times 2.17/.20 = 8.8 \times 10^7$$

and it is estimated that about 45 dynamic head units will be lost to friction

$$q = .0218 \times 5.03 \times 10^6/(2 \times 32.2 \times 144) = 11.85 \text{ lb/in}^2$$

Friction loss = 45 x 11.85 = 535 lb/in^2.

Pump pressure rise

$$6400 - 2500 - 2100 + 535 = 2335 \text{ lb/in}^2$$

Pump power

$$30.0 \times 10^6 \times .0218 \times 2335 \times 144/(778 \times 3415) = 83 \text{ Mw}$$

Since the cavity steam gives up 760 Btu/lb and the circulating water gives up 100 Btu/lb in cooling from 650°F to 550°F, the ratio of circulating water flow to cavity steam flow is 760/100 = 7.6.

Assuming that 500°F saturated steam (1202 Btu/lb) is supplied to the turbines and that it is returned as 100°F feed water (68 Btu/lb) the ratio of circulating water flow to turbine steam flow is (1202 - 68)/100 = 11.3.

Figure 2 illustrates an alternative system that does not have a circulating water loop. Instead, the cavity steam gives up heat directly to the turbine steam in super heater, boiler and condenser heat exchangers. Performance of the system will be about the same as that estimated for the circulating pressurized water system.

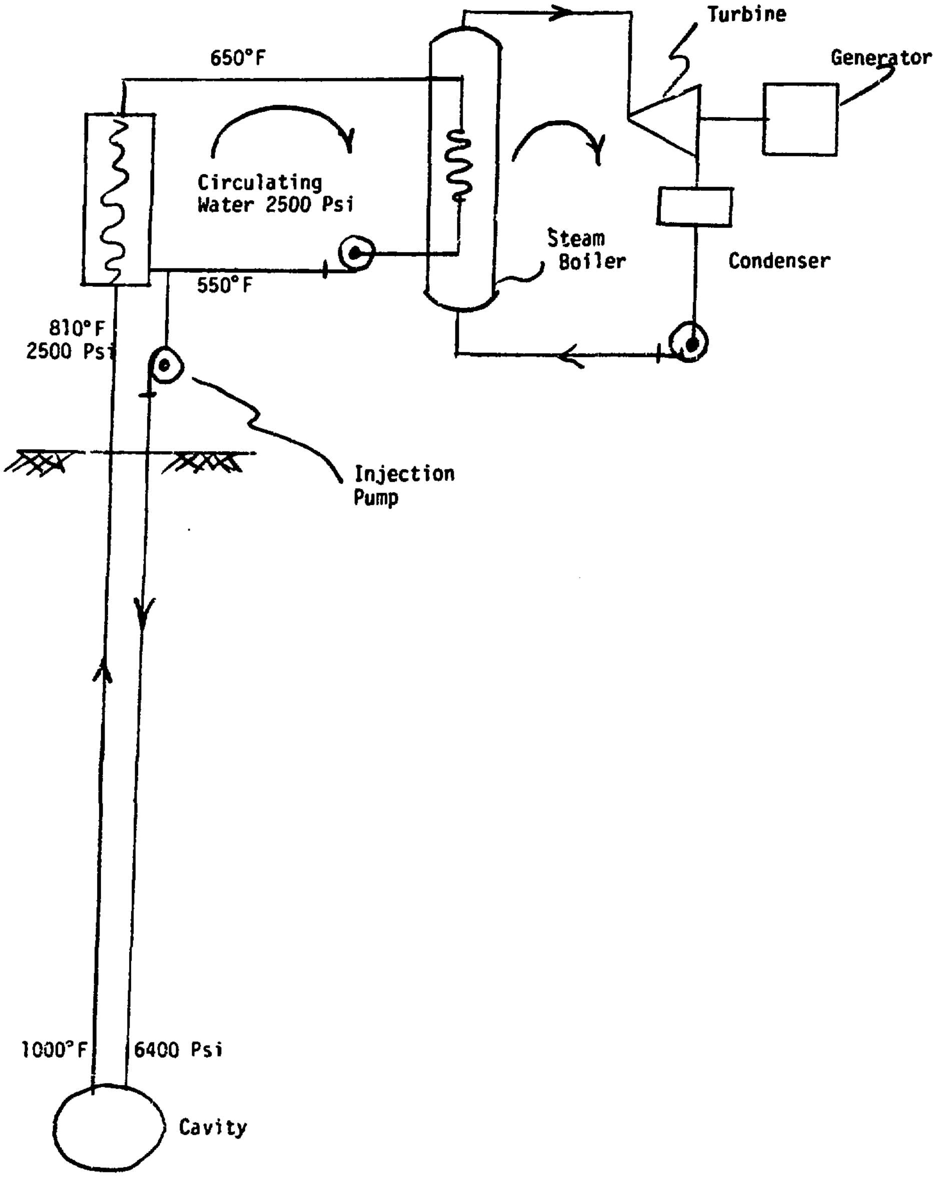


Figure 1. 2500 Psi Pressurized Water System

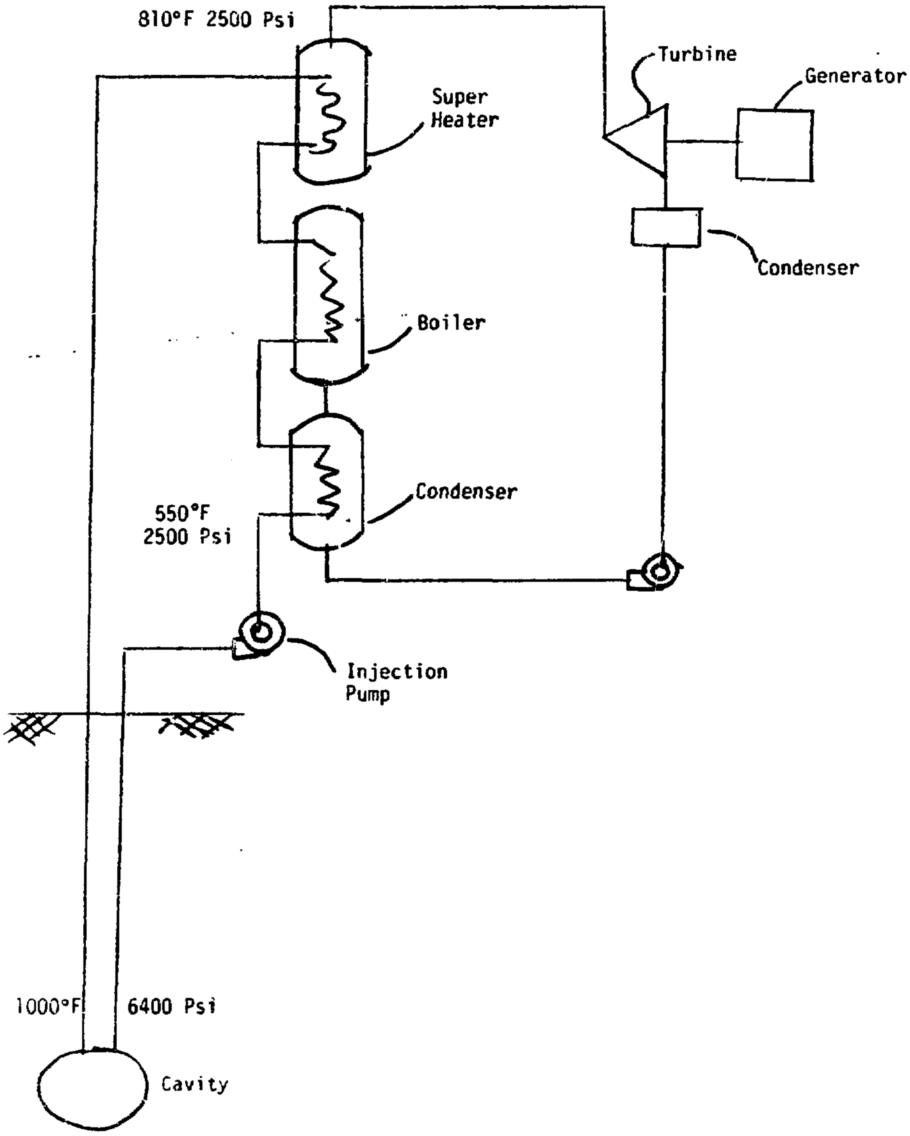
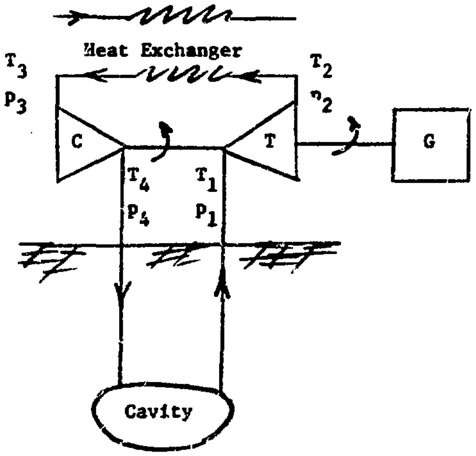


Figure 2. 2500 Psi Steam Heat Exchanger System

B.2 GAS TURBINE TYPE CYCLE FOR POWER GENERATION (L. Gore)

Steam turbine systems operating on the Rankine cycle are probably best suited for conversion of thermal energy generated in deep cavities to electrical power. However, it is interesting to consider the possibilities of using a gas turbine Brayton cycle for energy conversion. Such a system is illustrated in the following diagram.



Hot gas at about 1000°F flows from the cavity to the gas turbine T. Expanding through the turbine, the gas produces power to drive the compressor C and the generator G. The exhaust from the turbine passes through a heat exchanger where it is cooled to around 200°F by water from a river or cooling tower. The 200°F gas is then compressed to cavity pressure by the compressor and returned to the cavity.

There are two major undesirable aspects of such a system. First, the temperature range between 1000°F and 200°F is not large enough to yield a good thermal efficiency and second, the pressure level of 6400 lb/in^2 for the cavity operating pressure is much too high for reasonable design of gas turbine elements.

The thermal performance of the system was estimated by assuming the large turbines and compressors could operate at 90 percent internal efficiency. Pressure drop through the heat exchanger was neglected. With these conditions the maximum thermal efficiency is slightly less than 17 percent. The cycle pressure ratio at best efficiency depends upon the value of γ for the gas; for $\gamma = 1.67$ it is about 2.5 and for $\gamma = 1.40$ about 4.0

The thermal performance of the system can be estimated as follows:

x = turbine and compressor pressure ratios
C_p = specific heat at constant pressure
γ = ratio of specific heats
$Y = x^{(\gamma-1)/\gamma}$
e = turbine and compressor efficiencies

The temperature drop corresponding to work performed in the turbine is

$$T_1 - T_2 = T_1(1 - Y^{-1})e$$

and the temperature rise corresponding to work performed in the compressor is

$$T_4 - T_3 = T_3(Y-1)/e$$

The net work available to drive the generator is

$$C_p(T_1 - T_2 - T_4 + T_3)$$

per unit mass of gas. The total energy removed from a unit mass of gas is

$$C_p(T_1 - T_4)$$

and the thermal energy conversion efficiency is

$$(T_1 - T_2 - T_4 + T_3)/(T_1 - T_4)$$

B.3 PIPE SIZES AND PUMPING POWER (L. Gore)

B.3.1 Introduction

In connection with the examination of various gases as possible working fluids for the deep cavity power generating systems, it is of interest to determine the pumping power and pipe size required to circulate the gas.

B.3.2 Assumptions

The plant thermal efficiency is 30 percent corresponding to a heat rate of 6700 MW.

The gas leaves the cavity at 6400 lb/in^2 and 1000°F and is cooled to 500°F before it enters the return pipes. Gas pressure drop is assumed to be a small fraction of the cavity pressure.

Pressure loss in the heat exchanger is assumed equal to 50 percent of the total loss in the up and down pipes. 85 percent is assumed for the efficiency of the pump.

B.3.3 Conclusions

For the conditions assumed the pumping power depends only on the pressure drop around the circuit expressed as a fraction α of the cavity pressure and on the value of γ for the gas

α		.01	.03	.10
P,	, $\gamma = 1.40$	45	135	450
	, $\gamma = 1.67$	64	190	640

Pipe diameters depend on the properties of the gas. Diameters calculated for H_2, N_2 and A are shown in the following table.

α		.01	.03	.10
D, ft	H_2	6.4	5.2	4.2
	N_2	11.3	9.0	7.2
	A	14.0	11.1	8.9

B.3.4 Analysis

The mass flow rate of the gas is

$$\dot{M} = kWt \times 3415/(\Delta T\ C_p) \qquad \text{lb/h}$$

and the power required for pumping, assuming cooled gas at the pump inlet, is

$$P = kWt\ \alpha \frac{T - \Delta T}{e\Delta T}\ \frac{\gamma - 1}{\gamma} \qquad \text{kW}$$

α is the fraction of cavity pressure p which is lost in the loop, i.e., up and down pipes and heat exchanger. Since α is assumed to be small the pressure loss in the up pipe can be written as

$$\frac{nG^2v}{2g}$$

where v is the specific volume of the gas in the cavity and n is the number of velocity heads lost. The loss in the down pipe will be the same except that v corresponds to the temperature at the outlet of the heat exchanger

$$\frac{nG^2v}{2g}\ \frac{(T - \Delta T)}{T}$$

Adding 50 percent to each of these for an assumed heat exchanger pressure drop the total drop around the gas flow loop is

$$\alpha p = 1.5 \frac{nG^2 v}{2g} \left[1 + \frac{T - \Delta T}{T}\right]$$

Thus, G is determined and the size of the pipes can be obtained.

The value of n depends upon the value of the wall friction factor f and the length to diameter ratio (L/D) for the pipe

$$n = 4f \frac{L}{D} + 3$$

where the factor 3 has been added to account for fixed losses other than wall friction.

The value of f depends upon the Reynolds number for the flow in the pipes. Reynolds numbers for flows of interest have values in the neighborhood of 10^8 and as f does not change significantly with Reynolds number changes in this range a constant value of .003 has been used for f in the calculations.

Results of calculations for three gases using $\alpha = .03$ are shown in the following table.

	H_2	N_2	A
R, ft lb/lb	767	55.2	38.7
C_p, Btu/lb-F	3.42	.247	.124
γ	1.40	1.40	1.67
$\dot{M}$, lb/h	$13.4x10^6$	$185x10^6$	$369x10^6$
P, MW	135	135	190
n	18.1	11.8	10.1
v, ft^3/lb	1.215	.0875	.0614
G, lb/ft^2 - sec	180	820	1070
A, ft^2	21	63	96
D, ft	5.2	9.0	11.1

B.3.5 Symbols

p	gas pressure in cavity, 6400 lb/in^2
Δp	pressure drop in up and down pipes and heat exchanger
α	$\Delta p/p$
T	gas temperature in cavity, 1000°F
ΔT	gas temperature drop in heat exchanger, 500°F
v	specific volume
R	gas constant per unit mass
C_p	gas specific heat at constant pressure
γ	gas ratio of specific heats
P	pump power required
$\dot{M}$	gas mass flow rate
G	gas mass flow rate per unit area
g	gravitational constant
L	pipe length, 6560 ft
D	pipe diameter
f	pipe friction factor
n	number of dynamic heads lost in friction
e	pump mechanical efficiency

B.4 PRELIMINARY ESTIMATE OF SIZE, WEIGHT AND COST OF PRIMARY LOOP HIGH PRESSURE PIPES (L. Gore)

B.4.1 Introduction

Various methods have been suggested for utilizing the thermal energy generated in the cavity. Of these, probably the most simple method is to use pipes to bring hot cavity steam to the surface where heat is removed from it in a heat exchanger before it is returned to the cavity via another pipe or pipes. Such systems will generally be one of the following types.

1. Single phase systems in which superheated steam from the cavity passes through a heat exchanger and returns to the cavity as cooler steam. Circulation is produced by a compressor and by the pressure difference due to the difference in density between the steam in the "down" and "up" pipes.

2. Two phase systems in which superheated steam from the cavity is condensed to liquid in a heat exchanger and returned to the cavity by a pump. Pumping power tends to be small because of the small liquid volume flow rate and because of the large pressure difference produced by the large difference between density of the liquid and density of steam. By addition of pumping power the operating pressure in the heat exchangers can be reduced and more pressure drop made available for overcoming friction in the "up" pipes.

The pipes must be designed to operate at a pressure difference equal to the pressure in the cavity. At the present time uncertainties in the mechanics of the overburden pressure indicate that it is inadvisable to assume that the overburden can be used to reduce the pressure difference the pipe must withstand. And, in any case, the pipe must withstand the full pressure difference at its upper end when the pipe is "shut-off" at the upper end.

Allowable stress in the "up" pipe wall is fixed by the temperature of the steam in the cavity. In pipe systems designed for a high friction pressure drop there may be a significant temperature drop due to throttling; but, this cannot be used advantageously because it will not exist at low rates of steam flow.

Higher stresses can be used in the "down" pipes because the temperature of the steam or liquid is lower than the temperature in the cavity. At present it seems advisable to make the down pipes identical to the "up" pipes for interchangeability and because it may be desirable to reverse the flow periodically to remove salt deposits.

B.4.2 Object

The object of this report is to present estimates of size, weight, and cost of simple primary loop high pressure pipes for single phase and two phase systems.

B.4.3 Assumptions

Average cavity steam conditions are 550°C and 320 bars. Variations in pressure and temperature are not considered.

Rate of steam flow from the cavity is based on generating 2000 MW(e) at an efficiency of 30 percent.

In the single phase system it is assumed that steam is returned to the cavity at 400°C. Power for circulating the steam is limited to 100 MW.

In the two phase system the pressurized water is assumed to be at 170 bars and water is returned to the cavity at 315°C. 25% of the pressure drop available for friction in the "up" pipe is reserved for control at the throttle valve.

The inside surface of the pipes is assumed to be rough due to deposition of impurities in the steam. An absolute roughness of 0.001 ft is assumed, corresponding to smooth concrete. (Marks' ME Handbook, Ed. 6, Table 4, p. 3-71).

Stainless steel pipes having a maximum wall thickness of 2.0 in are assumed. Cost of the pipes is assumed to be at least $1 per lb.

The "down" pipes are assumed to be the same as the "up" pipes for interchangeability and possible reversal of flow.

B.4.4 Results

The cost of the all steam single phase system is too high and only the two phase pressurized water system appears to be feasible. The two systems are compared in the following table.

	Single Phase All Steam	Two Phase Pressurized Water
Maximum wall thickness, in	2.0	2.0
Pipes inside diameter, in.	7.7	7.7
Number of pipes	129	36
Pump power,	115×10^3	24×10^3
Total weight of pipes, lb	270×10^6	76×10^6
Total cost of pipes at $1/lb	\$270 $\times 10^6$	\$76 $\times 10^6$

Single pipe systems require pipe walls that are probably too thick to be feasible. But, they offer a potential method for significant reduction in weight as shown in the following table.

	Single Phase All Steam	Two Phase Pressurized Water
Number of pipes	1	1
Inside diameter, in	49.2	30.0
Wall thickness, in	12.21	7.50
Total weight of pipes, lb	65×10^6	24×10^6

B.4.5 Analysis

B.4.5.1 Pipe Diameter

The ASME code for Pressure Piping specifies the following formula for pipe wall thickness:

$$t = \frac{pD}{2S + yp} + C$$

The value specified for the stress S for 1050°F (566°C) pipe wall temperature is 13100 lb/in^2. The value specified for y at this temperature is 0.4 for austenitic steels. C represents an allowance for corrosion and is specified as 0.065 in for pipes with welded joints (Marks' ME Handbook, Ed. 6, p. 8-157, 8-164).

The "Reactor Handbook", Vol. IV, p. 122, states the following relative to procurement and fabrication:

> "Vessel shells formed of carbon and low-alloy steels (SA-212, SA-201) may be as much as 8 in. in thickness and even more in special circumstances. Shells of other materials are usually restricted to much thinner walls because of difficulties involved in obtaining sound material at reasonable costs and because of the difficulties of fabrication. For example, the austenitic stainless steels (Type 304, 307) have an upper practical economic limit in the range from 2 to 3 in."

It is possible to clad carbon steel with layers of corrosion resistant material. However, preservation of the cladding at welded joints is a problem and since the long pipes can probably never be removed for inspection and repair after they have been put in place, it seems inadvisable to assume clad carbon steel can be used for the vertical pipes.

Assuming a value of 2.0 in for the maximum pipe wall thickness, the following are obtained for the pipe.

$D = 11.7$ in
$d = 7.7$ in
$a = 0.323\ \text{ft}^2$
$w = 220$ lb/ft

B.4.5.2 Pipe Friction

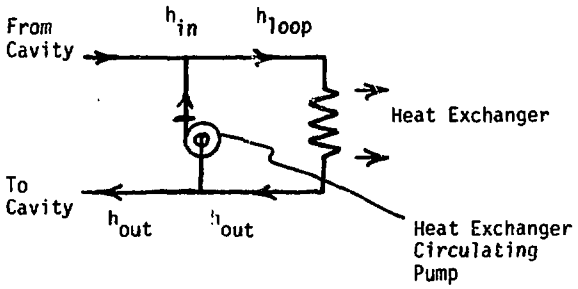
The pressure drop due to pipe friction can be approximated by the equation

$$\Delta p = 4f \frac{L}{d} \frac{G^2 \bar{v}}{2g}$$

if $\bar{v}$ is defined as the average specific volume of the fluid in the pipe. The friction factor f depends upon the Reynolds number for flow in the pipe and upon the roughness of the pipe surface. This absolute roughness is assumed to be 0.001 ft and for a 7.7 in diameter pipe the ratio of roughness to diameter is 0.00156. Reference to the friction factor data in Marks' ME Handbook, Fig. 18, p. 3-72, shows that for this roughness ratio the value of 4f is about 0.022 and is independent of Reynolds number above about 10^6. Calculations show that the single phase and two phase systems operating under conditions assumed for this analysis have Reynolds numbers which exceed this lower limit.

B.4.5.3 Heat Exchangers

In order to keep the size and cost of the heat exchangers within acceptable limits, it is necessary to circulate the hot fluid through the tubes at high mass velocity. In a practical sense, this requires that the hot fluid be recirculated through the tubes many times as shown in the following sketch.



The mass flow rate through the heat exchangers may be many times the rate of mass flow from the cavity. Thus, for purposes of analysis, it can be assumed that the heat exchanger fluid circulates continuously and that a smaller flow of hot cavity steam is continually added (and subtracted) to maintain the heat balance.

$$h_{in} - h_{out} = r(h_{loop} - h_{out})$$

where h is the enthalpy and r is the ratio of mass flow rate in the heat exchanger to mass flow rate of cavity steam.

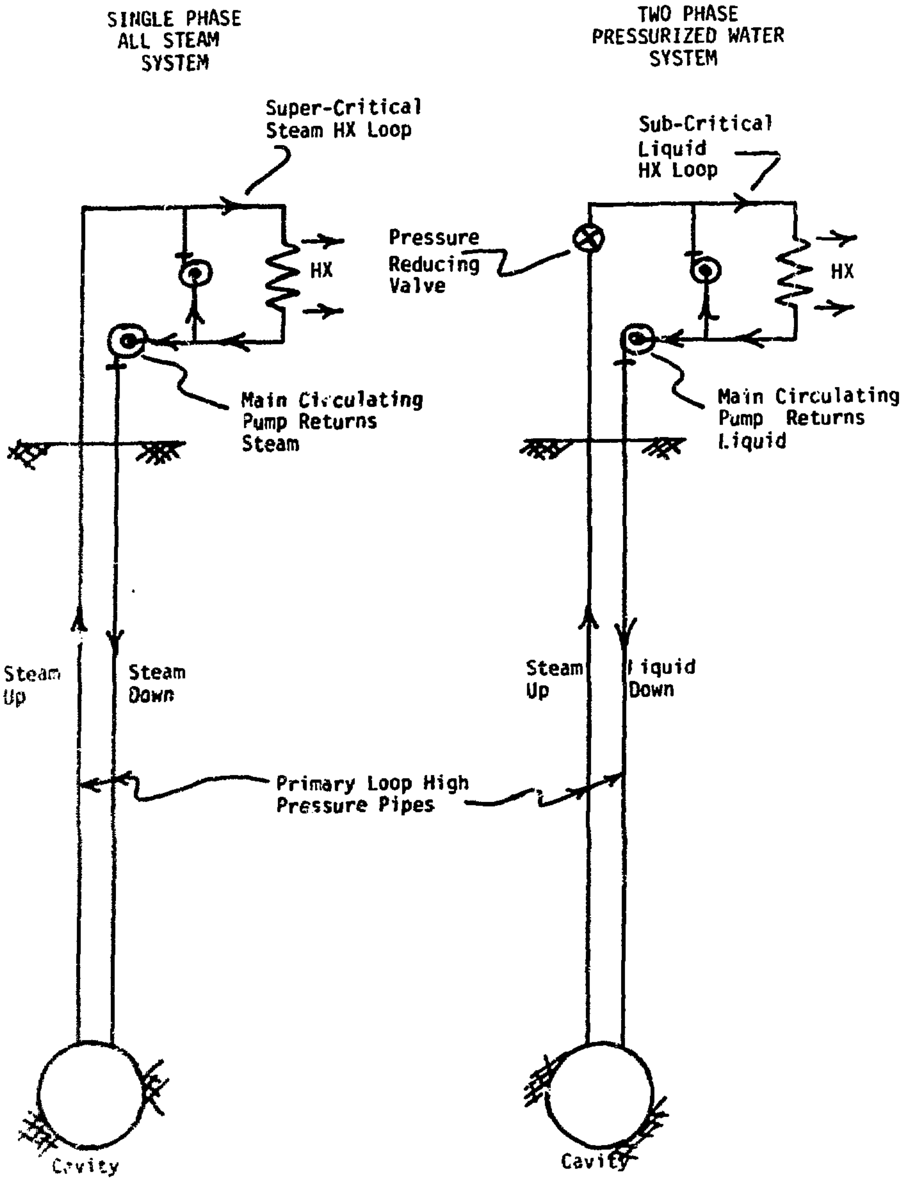
There are two principal ways in which the heat exchanger loop can be operated; either as an all steam loop or as an all liquid loop. In the all steam system the temperature of the exiting steam (condition h_{out}) is supercritical and the pressure in the heat exchanger is cavity pressure except for the "up" pipe gravity and friction pressure drops. In the all liquid system, the temperature of the water is sub-critical and the pressure of the water is maintained at a value sufficiently above the saturation pressure to prevent the possibility of boiling. Such a system is sometimes called a pressurized water system. As the pressure may be considerably less than cavity pressure the steam coming from the cavity is throttled to the heat exchanger pressure before it is mixed with the circulating water.

The super-critical system has the advantage of high temperatures in the heat exchanger and the disadvantage of high pressure. The opposite is the case for sub-critical systems.

B.4.5.4 Pipes and Pumps

The diagrams on the following page show how these two systems are operated when connected to the cavity with pipes. Main circulating pumps are shown in both systems; however, it should be noted that there is always some "self" pumping due to the higher density of the fluid in the "down" pipes.

In the single phase all steam system, steam from the cavity after giving up heat in the heat exchanger loop is forced back into the cavity as steam by the main circulating pump. Its performance, i.e., the size of the pipes


SINGLE PHASE ALL STEAM SYSTEM
TWO PHASE PRESSURIZED WATER SYSTEM
Super-Critical Steam HX Loop
Sub-Critical Liquid HX Loop
Pressure Reducing Valve
HX
HX
Main Circulating Pump Returns Steam
Main Circulating Pump Returns Liquid
Steam Up
Steam Down
Steam Up
Liquid Down
Primary Loop High Pressure Pipes
Cavity
Cavity

and permissible friction pressure drop is limited by the pumping power available. For preliminary investigation, the power has been limited to about 100 MW or about 5 percent of the plant output.

In the two phase pressurized water system it is assumed that the pressurized water is at 170 bars and that the liquid return temperature is 315°C. Most of the pressure difference between cavity pressure and the pressurized water is available to overcome friction in the "up" pipe; however, 25 percent of the drop available for pipe friction is reserved for drop across a pressure reducing valve used for control of the system. Pumping power is not limiting because the density of the pumped liquid is high and because there is a significant "self" pumping effect.

B.4.5.5 Performance--Multiple Pipes

The following tabulation shows the performance of the single phase and two phase systems using multiple 7.7 in diameter pipes. The "down" pipes are assumed identical to the "up" pipes.

	Single Phase All Steam	Two Phase Pressurized Water
Cavity pressure bars	320	320
Cavity temperature °C	550	550
Steam leaving HX bars	270	
Steam leaving HX°C	400	
Water leaving HX bars		170
Water leaving HX°C		315
h_{in} j/g	3251	3251
h_{out} j/g	2428	1365
$h_{in} - h_{out}$ j/g	823	1886
$\dot{M}$ lb/h	64.6×10^6	28.2×10^6
$\dot{M}$ lb/sec	17.9×10^3	7.83×10^3
v_b bottom cm^3/g	9.37	9.37

v_u top 270 bars	cm^3/g	11.10	
v_u top 205 bars	cm^3/g		14.67
$\bar{v}$	cm^3/g	10.24	12.02
$\bar{v}$	ft^3/lb	.1640	.1926
Δp_u bars		50	150
Δp_u	lb/in^2	725	1630
Δp_u gravity	lb/in^2	200	170
Δp_u friction	lb/in^2	525	1504
$4fL/d$		163	163
G^2		182×10^3	444×10^3
G lb/ft^2-sec		427	667
aG lb/sec per pipe		138	215
n		129	36.4
W total, up and down, lb		270×10^6	76×10^6
p_d top bars		300	220
v_d top	cm^3/g	4.40	1.38
v_d bottom	cm^3/g	4.00	1.36
$\bar{v}$	cm^3/g	4.20	1.37
$\bar{v}$	ft^3/lb	.0673	.0220
Δp_d gravity	lb/in^2	490	1490
Δp_d friction	lb/in^2	220	170
p_d top bars		301.4	219.0
Δp pump bars		31.4	49.0
Δp pump	lb/in^2	455	710
v pump in	cm^3/g	4.55	1.39
v pump out	cm^3/g	4.40	1.39
$\bar{v}$ pump	ft^3/lb	.0718	.0223
Pump power	kW	115×10^3	24.2×10^3
μ_u micropoise		350	343
μ_u lb/sec-ft		23×10^{-6}	23×10^{-6}
R_u		1.2×10^7	2.0×10^7
μ_d micropoise		450	900
μ_d lb/sec-ft		30×10^{-6}	60×10^{-6}
R_d		9.0×10^6	7.8×10^6

B.4.5.6 Performance—Single Pipes

It is interesting to determine the size and weight of a single pipe that would replace the multiple pipes if the minimum pipe wall thickness restriction could be removed. Using the conditions for the previous calculations the following results are obtained

	Single Phase All Steam	Two Phase Pressurized Water
4f	0.014	0.015
d ft	4.10	2.50
d in	49.2	30.0
t in	12.21	7.50
w lb/ft	6794	2544
W total, up and down lb	65×10^6	24×10^6

SYMBOLS

t	pipe wall thickness
p	pressure
Δp	pressure difference
D	outside diameter
d	inside diameter
a	area, cross section, inside
S	allowable stress
L	pipe length (4750 ft)
f	friction factor
v	specific volume
$\bar{v}$	average specific volume
$\dot{M}$	mass flow rate
G	mass velocity
g	gravity constant (32.2 ft/sec^2)
n	number of pipes in parallel
W	weight of pipes (total up and down)
w	weight of pipe per unit length
μ	viscosity
R	Gd/μ, Reynolds number
h	enthalpy
Δh	enthalpy difference

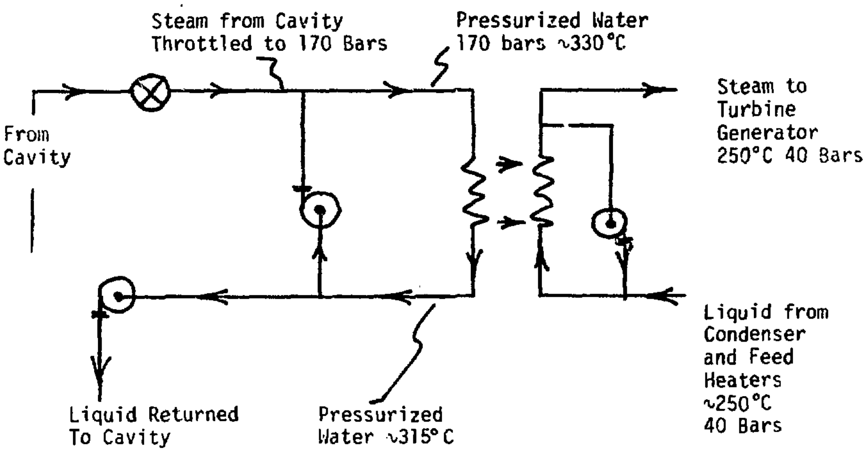
SUBSCRIPTS

u	"up" pipe
d	"down" pipe

B.5 PRESSURIZED WATER HEAT EXCHANGERS (L. Gore)

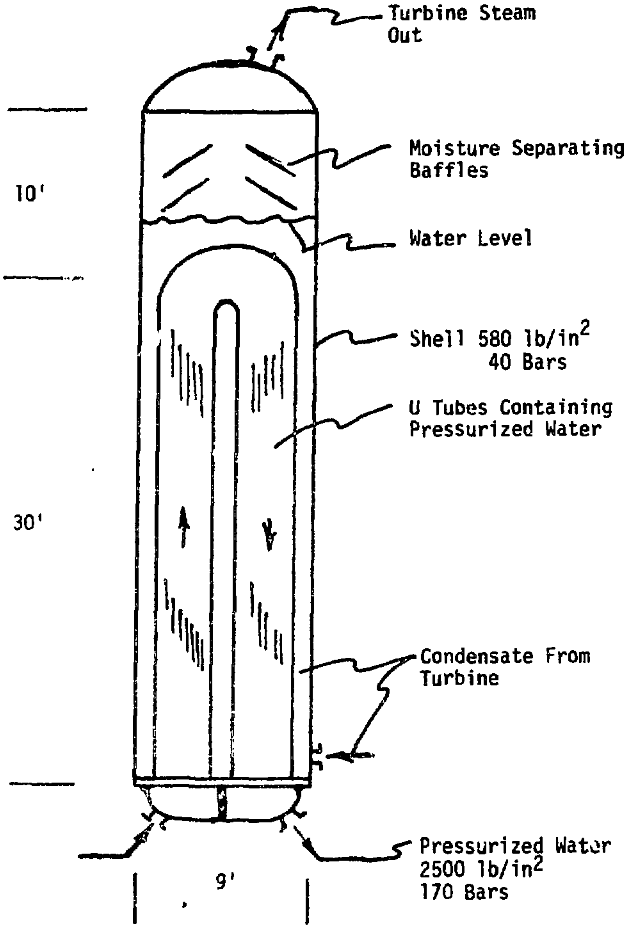
B.5.1 Introduction

In the pressurized water system for removing heat from the cavity steam, the cavity steam is mixed with pressurized water which is circulated through heat exchangers. Steam for operating the turbine generators is produced on the other side of the heat exchangers. The following diagram shows how the system operates.



The following diagram shows a typical form of construction for a pressurized water heat exchanger. Various types of construction and arrangement are possible and are described in the Reactor Handbook, Vol. IV, Ed. 2, Chap. 3, Wiley.

The external shell which is designed for 40 bars pressure is about 9 ft in diameter. The vertical height (overall length) is about 50 ft.



Pressurized Water Heat Exchanger

Pressurized water enters one side of the high pressure header located at the bottom. From there it enters U tubes with legs about 30 ft long and returns to the other side of the header.

Feed water occupies the space between the tubes and the shell. Steam is generated in the water and after passing through moisture separating baffles at the top of the unit it goes to the turbines.

B.5.2 Object

The object of this report is to examine the preliminary design and performance of a pressurized water heat exchanger.

B.5.3 Assumptions

Basic power plant rating is 2000 MW(e) at a thermal efficiency of about 30 percent (6700 MW(t)).

Average cavity steam conditions are 320 bars 550°C. Pressurized water conditions are 170 bars and 315°C at the exit. Turbine generator steam conditions are dry saturated steam at 250°C and ~40 bars with the feed water returned at 250°C.

The heat exchanger is fabricated from Cr-Mo carbon steel with stainless steel cladding on the inside of the tubes and high pressure header for corrosion prevention. Tubes are 2.5 in outside diameter and are located in a 3.5 x 3.5 in square array in the tube sheets.

B.5.4 Results

Number of heat exchanger units required	59
Weight each, lb	311×10^3
Total weight for 2000 MW(e) plant, lb	18×10^6
Total cost at $3/lb	$\$54 \times 10^6$
Cost $/KW(e)	27

B.5.5 Discussion

The Reactor Handbook, Vol. IV, Ed. 2, p. 557, Wiley, states that the YANKEE PWR nuclear plant uses four pressurized water heat exchangers to transfer 392 MW(t). This is about 100 MW(t) per heat exchanger which scales to 67 units for the proposed 6700 MW(t) 2000 KW(e) plant.

B.5.6 Analysis

B.5.6.1 Tube Design

The 30 ft leg U tubes are assumed to have an outside diameter of 2.5 in and to be located on 3.5 in centers in a square array.

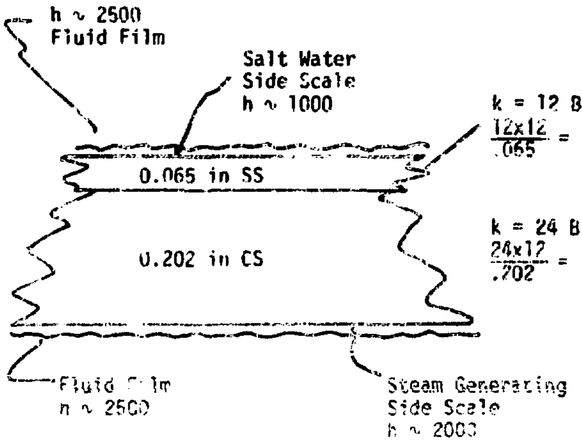
The tube wall thickness is determined according to the ASME code for Pressure Piping, Marks' ME Handbook, Ed. 6, p. 8-157, 8-164, for operation at 2500 lb/in^2 (40 bars) and <650°F (<343°C).

Cr-Mo carbon steel is assumed with an operating stress of 15,000 lb/in^2. A layer of corrosion resistant material such as stainless steel having a thickness of 0.065 in is assumed added to the inside of the tubes.

Thickness carbon steel, in	0.202
Thickness cladding steel, in	0.065
Thickness total steel, in	0.267
Tube outside dia., in	2.500
Tube inside dia., in	1.966
Tube average dia., in	2.333
Tube average surface area, ft^2/ft	0.585
Tube inside flow area, in^2	3.04

B.5.6.2 Tube Heat Transfer

The following diagram shows the values assumed for the various factors which control the heat transfer across the tube walls.



The fluid film heat transfer coefficient for the inside of the tube is based on a mass velocity of 1.5×10^6 lb/ft^2-h. Ref.: Reactor Handbook, Vol. IV, Ed. 2, p. 42, Wiley. The coefficient assumed for the boiling water steam generating side can be obtained with a similar mass velocity and use of baffles.

Combination of the above conductances gives 290 Btu/ft^2-h-F for the overall conductance.

B.5.6.3 Heat Exchanger Performance

Cavity Steam	
Average pressure, bars	320
Average temperature, °C	550
Pressurized Water	
Pressure, bars	170
Temperature, leaving HX, °C	315
Temperature, Throttled Steam, 170 bars	490
h, in, throttled steam, j/g	3251
h, out, liquid, j/g	1481
h, change, j/g	1770
Cavity steam rate, 6700 MW(t)	
g/sec	3.785×10^6
lb/h	30.0×10^6
c_p, 170 bars, 320-340°C j/g-C	6.58
r, ratio HX liquid flow to cavity steam flow	18.3
Temperature change, °C	15
Temperature, liquid into HX, °C	330
HX temperature difference, high, °C	80
HX temperature difference, low, °C	65
HX mean temperature difference, °C	72
U, Btu/h-ft^2-F	290
Total HX surface area, ft^2	607×10^3

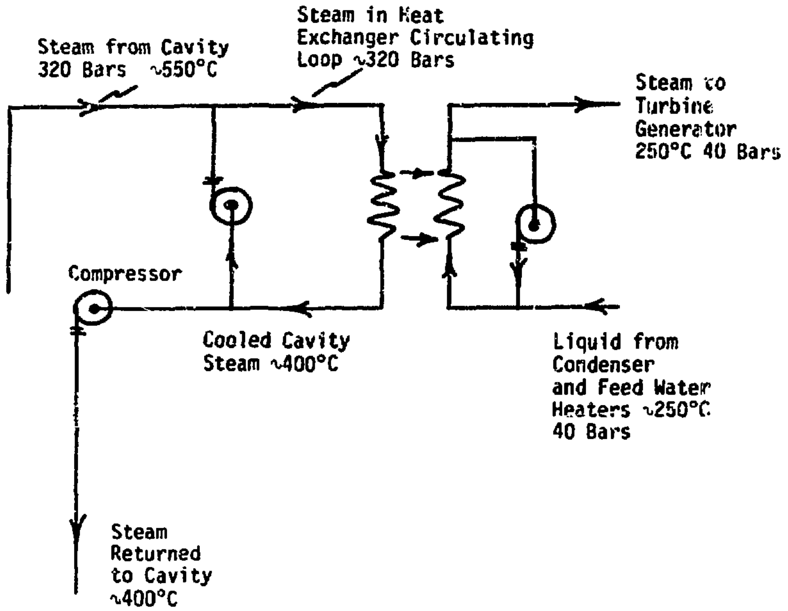
Head effective inside dia., ft	8
Head utilization factor	0.9
Head area for tubes, ft^2	50
Head area per tube, in^2	12.24
Tube legs per head	588
Tube area per ft, ft^2	.585
Tube area per head, ft^2	10,320
HX units required	59
Tube flow area per tube, in^2	3.04
Tube flow areas per head, ft^2	6.20
Tube flow area total, ft^2	366
Total circulating water flow at 1.5×10^6 lb/ft^2-h, lb/h	550×10^6
$\bar{v}$, average specific volume, tube, cm^3/g	1.487
$\bar{v}$, average specific volume, tube, ft^3/lb	0.02383
G lb/ft^2-h	1.5×10^6
G lb/ft^2-sec	417
$G^2\bar{v}/(2g)$, lb/in^2	.45
μ, viscosity, micropoise	1100
μ, viscosity, lb/h-ft	.266
Gd/μ Reynolds number	$.92 \times 10^6$
4f (Marks' ME Handbook, ed 6, p. 3-72)	.015
4fL/d	5.5
Fixed loss (estimate)	5
Total loss	10.5
Circulating pump	
Pressure rise, lb/in^2	4.73
Power, kW	3200
HX tube weight, lb/ft^2	11.53
HX tube weight for one unit including 25 percent for high pressure head and fittings, lb	149×10^3
Boiler temp, °C	250
Boiler dia, in	120
Boiler pressure, lb/in^2	580
Boiler allowable stress, lb/in^2	15,000

Boiler shell thickness including .065 in for corrision, in	2.39
Boiler shell weight (40 ft long) one unit including 25 percent for head and fittings	162×10^3
Totals	
Boiler shell and tubes, one unit, lb	311×10^3
57 units, lb	17.7×10^6

B.6 ALL STEAM HEAT EXCHANGERS (L. Gore)

B.6.1 Introduction

In the all steam heat exchanger system used for removing heat from the cavity steam, the cavity steam is circulated through heat exchangers and returned to the cavity as steam at a lower temperature. Steam for operating the turbine generators is produced on the other side of the heat exchangers. The following diagram shows how the system operates.



The type of construction is generally similar to that used for pressurized water heat exchangers. Refer to Appendix Section B.5, "Pressurized Water Heat Exchangers." L. A. Gore, and Reactor Handbook, Vol. IV, Ed. 2, Chapter 3, Wiley.

Increasing the pressure from 170 bars used for the pressurized water heat exchanger to 320 bars makes it advisable to reduce the principal dimension of the high pressure head from 8 ft to 8 x 170/320 = 4.25 ft. Similarly, the average leg of the U tubes is reduced to 16 ft and overall length of the exchanger becomes about 27 ft. The outer shell which must withstand turbine steam pressure of 40 bars is about 5 ft in diameter.

B.6.2 Object

The object of this report is to examine the preliminary design and performance aspects of an all steam heat exchanger operating at cavity steam pressure.

B.6.3 Assumptions

Basic power plant rating is 2000 MW(e) at a thermal efficiency of about 30 percent (6700 MW(t)).

Average cavity steam conditions are 320 bars and 550°C. Steam is assumed to leave the heat exchangers at the super critical temperature of 400°C.

Turbine generator steam conditions are dry saturated steam at 250°C and ~40 bars with the feed water returned at 250°C.

The heat exchanger is fabricated from Cr-Mo carbon steel with stainless steel cladding on the inside of the tubes and high pressure header for corrosion prevention. Tubes are 1.0 in outside diameter and are located in a 2.0 x 2.0 in square array in the tube sheets.

B.6.4 Results

Number of heat 5 ft dia x 27 ft long exchanger units required	154
Weight, lb/unit	44,600
Total weight, 2000 MW(e) plant, lb	6.9×10^6
Total cost at $4/lb	$\$27.6 \times 10^6$
Cost, $/KW(e)	14

B.6.5 Analysis

B.6.5.1 Tube Design

The 16 ft leg U tubes are assumed to have an outside diameter of 1.0 in and to be located on 2.0 centers in a square array.

Assuming the maximum temperature of the steam in the circulating loop is 450°C and that the turbine steam side of the tubes is at 250°C, the average temperature of the tube walls is 350°C. The allowable stress for Cr-Mo carbon steel tubes at this temperature is 15,000 lb/in^2. Refer to ASME code for Pressure Piping, Marks' ME Handbook, Ed. 6, p. 8-157, 8-164. A layer of corrosion resistant steel 0.050 in thick is assumed added to the inside of the tubes.

Thickness carbon steel, in	0.146
Cladding, in	0.050
Total, in	0.196
Tube, outside dia, in	1.00
Tube, inside dia, in	0.60
Tube, average dia, in	0.80

Tube, average surface area, ft^2/ft	0.210
Tube, inside flow area, in^2	0.282

B.6.5.2 Tube Heat Transfer

The tube wall thickness is about the same as the wall thickness used in analysis of the pressurized water heat exchanger. The thermal conductances of the elements are as follows. Units are Btu/ft^2-h-F.

Cavity steam side film (G$\sim$1.5 lb/ft^2-h)	2500
Cavity steam side scale	1000
0.050 in stainless steel 12x12/.050	2880
0.146 in carbon steel 24x12/0.146	1970
Turbine steam side scale	2000
Turbine steam side film	2500

The fluid film heat transfer coefficient for the inside of the tube is based on the assumption of a mass velocity of about 2.0 x 10^6 lb/ft^2-h. Ref., Reactor Handbook, Vol. IV, Ed. 2, p. 42, Wiley. The coefficient for the boiling water steam generating side can be obtained with a lower mass velocity.

Combinations of the above conductances gives 322 Btu/ft^2-h-F for the overall conductance.

B.6.5.3 Heat Exchanger Performance

Cavity steam average pressure, bars	320
Cavity steam temperature, °C	550
Heat exchanger	
Average pressure, bars	270
Steam mixture, in, °C	433

Steam mixture, out, °C	400
Steam mixture, change, °C	33
h, in j/g	3251
h, out j/g	2428
h, change j/g	823
Cavity steam rate, 6700 MW(t)	
g/sec	8.15×10^6
lb/h	64.5×10^6
r, ratio, HX flow to cavity flow	2.2
Turbine steam	
Pressure, bars	40
Temperature, °C	250
HX temperature difference, high, °C	183
HX temperature difference, low, °C	150
HX mean temperature difference, °C	166
U, Btu/ft^2-h-F	322
Total HX surface area, ft^2	237×10^3
Head effective inside dia, ft	4.25
Head utilization factor	0.9
Head area for tubes, ft^2	12.7
Head area per tube, in^2	4.0
Tube legs per head	457
Tube area per ft, ft^2	0.210
Tube area per head, ft^2	1540
HX units required	154
Tube flow area per tube, in^2	0.282
Tube flow area per head, ft^2	0.448
Tube flow area total, ft^2	69.0
Total circulating steam flow at 2.0×10^6 lb/ft^2-h, lb/h	138×10^6
$\bar{v}$, average specific volume, tube cm^3/g	6.40
$\bar{v}$, average specific volume, tube ft^3/lb	0.103
G, lb/ft^2-h	2.0×10^6
G, lb/ft^2-sec	555
$G^2\bar{v}/(2g)$, lb/in^2	4.9

μ, viscosity, micropoise	320
μ, viscosity, lb/h-ft	0.077
Gd/μ Reynolds number	1.3×10^6
4f (Marks' ME Handbook, 3d 6, p 3-72)	0.015
4f L/d	9.6
Fixed loss (estimate)	5
Total loss	14.6
Circulating pump	
Pressure rise, lb/in^2	72
Power, KW	26×10^3
Tube weight	
lb/ft^2	8.5
One unit including 25 percent for high pressure head and fittings, lb	16,400
Boiler weight (turbine steam)	
Temperature, °C	250
Pressure, bars	40
Pressure, lb/in^2	580
Diameter, ft	5.0
Allowable stress, lb/in^2	15,000
Shell thickness, including .065 in for corrosion, in	1.23
Shell weight, 27 ft long and including 25 percent for head and fittings, lb	28,200
TOTALS	
Tube and boiler shell, one unit, lb	44,600
154 units, lb	6.9×10^6

B.7 PACER THERMAL EFFICIENCY (L. Gore)

B.7.1 Introduction

Plans for the PACER system for power generation are based on producing steam at an average temperature of about 525°C (see Section A.3). Since the sink for heat rejection is the atmosphere, the lower temperature for the cycle is about 20°C. The Carnot cycle, illustrated in Figure 1, can be used to define the ideal maximum thermal conversion efficiency for a system operating between temperature limits of T_1 and T_2 [2].

$$e(\text{Carnot}) = (T_1 - T_2)/T_1$$

Using

$$T_1 \sim 800 \text{ K}$$

$$T_2 \sim 300 \text{ K}$$

$$e(\text{Carnot}) \sim 0.62$$

Ideally, steam from the cavity could be expanded through a turbine-generator to produce electricity. It would then be condensed by atmospheric cooling and returned to the cavity as a liquid. Such a cycle is illustrated by the ideal Rankine cycle [1] shown in Figure 2. Superheated steam from the cavity, point 1, is expanded at constant entropy in the turbine to the condenser condition, point 2. Heat is removed by atmospheric cooling along line 2-3 and the liquid at point 3 is returned to the cavity. The ideal efficiency is

$$e(\text{Rankine}) = \frac{h_1 - h_2}{h_1 - h_3}$$

Neglecting small corrections due to the depth of the cavity below the surface and assuming for

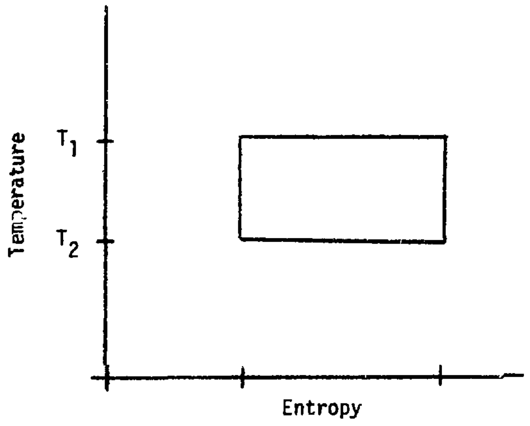


Figure 1. Carnot Cycle

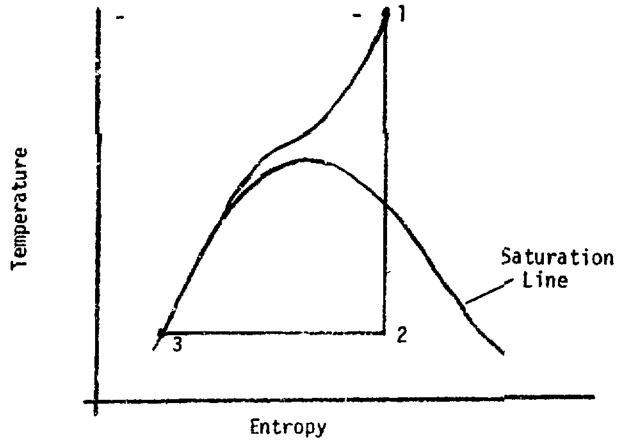


Figure 2. Rankine Cycle

point 1, 525°C, 240 bars
point 2, 2 inches Hg absolute
pressure ($\sim$39°C)

the basic Rankine cycle efficiency is

$$e(\text{Rankine}) \sim 0.44$$

If this cycle efficiency is multiplied by 0.75 to approximately account for turbine, pump and generator losses, the overall efficiency measured at the electrical output terminals is

$$e(\text{Rankine, term}) \sim 0.33$$

The poor performance of the Rankine cycle relative to the Carnot cycle is due to the fact that most of the heat added is added at temperatures significantly less than the top temperature, T_1. This condition can be improved by using a regenerative cycle [1], wherein steam is extracted from the turbine and used to heat the condensate. The diagram of Figure 3 shows the regenerative cycle assuming continuous extraction between point 2 where the expansion line crosses the saturation line and the condenser condition at point 3. The efficiency is

$$e(\text{regen}) = \frac{(h_1 - h_3) - (h_6 - h_4)}{h_1 - h_6}$$

and for conditions the same as those used for the Rankine cycle

$$e(\text{regen}) \sim 0.52$$

$$e(\text{regen, term}) \sim 0.39$$

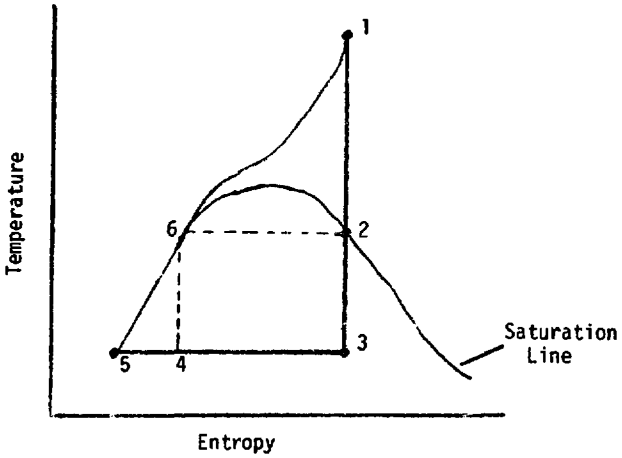


Figure 3. Regenerative Cycle

In spite of the prospects of obtaining a good thermal efficiency, it is generally considered undesirable to use the steam from the cavity to drive the steam turbines directly for the following reasons:

1) Salt in the cavity steam may deposit in the turbine passages and spoil the performance of the turbine. It may also cause chemical damage.
2) The turbine will become contaminated with radioactive materials.
3) There is probably more danger of leakage of undesirable materials to the atmosphere from a relatively complex machine such as a turbine.

If the cavity steam is not used in direct contact with the turbines, it must be used in heat exchangers (boilers) to generate secondary steam which is free of salt and radioactive materials for driving the turbines (see Appendix Sections B.1 and B.5). In designing such a system the important considerations appear to be:

1) The steam taken from the cavity must be condensed and returned to the cavity as a liquid in order to minimize the requirements for pumping.
2) High pressure drop must be available in the steam pipes leading from the cavity to the surface for overcoming friction in the pipes so that the complexity and cost of the pipes can be minimized.

B.7.2 Object

The object of this report is to investigate the effect of cavity pressure on the electrical output thermal conversion efficiency of pressurized water PACER systems.

Calculations are performed for cavity minimum pressures of 160, 200, 260 and 340 bars. Three secondary side steam cycles are investigated,

Rankine, saturated steam
Regenerative, saturated steam
Regenerative, superheated steam.

B.7.3 Assumptions

Temperature in the cavity

average 520°C
minimum 470°C
maximum 570°C

Pressure in the cavity

minimum is twice the pressurized water pressure
maximum is 20 percent greater than the minimum
maximum is 75 percent of overburden pressure

Average temperature of the pressurized water in the heat exchanger is 20°C less than the pressurized water saturation temperature.

Average temperature difference across the heat exchanger is approximately 40°C. The saturation temperature of the secondary steam is 40°C less than the average temperature of the pressurized water.

The superheated secondary steam has a temperature 50°C less than the minimum-temperature minimum-pressure cavity steam after it is throttled (constant enthalpy) to the pressurized water pressure.

B.7.4 Results

The following tabulation shows the variation of thermal conversion efficiency with cavity pressure and type of steam cycle.

Cavity pressure, minimum bars	340	260	200	160
Pressurized water pressure, bars	170	130	100	80
Efficiency				
Rankine cycle saturated steam	.251	.254	.250	.244
Regenerative cycle saturated steam	.299	.297	.288	.278
Regenerative cycle superheated steam	.300	.308	.305	.295

Conclusions are:

1) The thermal efficiency does not change significantly over the range of cavity pressure investigated.
2) The regenerative cycles are significantly better than the Rankine cycle.
3) Improvement in efficiency produced by superheating is only significant at the lower cavity pressures.

B.7.5 Discussion

Efficiencies do not increase with increase in cavity pressure because of the larger amount of power required to pump the liquid back into the cavity. Pumping power, expressed as a fraction of the output power is shown in the following tabulation along with the approximate increment in thermal efficiency.

Cavity pressure, minimum, bars	340	260	200	160
Pump power, fraction	.078	.050	.032	.023
Approximate increment	.023	.015	.010	.007

Superheating at the higher cavity pressures does not improve efficiency significantly because the temperature rise available for superheating decreases. This occurs because the pressurized water saturation temperature is higher and because the temperature drop in throttling the cavity steam from cavity pressure to pressurized water pressure is greater.

B.7.6 Analysis

B.7.6.1 Efficiency Factors

Turbine efficiency is based on using a factor of 0.95 for the fixed losses and 0.87 for the internal efficiency when operating with dry steam. Correction for wet steam is based on the following. Actual moisture at the end of the expansion is estimated by adding 15 percent of the available energy to the exhaust energy. Where more than 10 percent moisture is predicted in the exhaust it is assumed that 50 percent of the moisture in excess of 10 percent has been removed by mechanical separation. The moisture correction factor is then computed from

$$mcf = f_d + f_w (1 - y/2)$$

where y is the corrected moisture in the exhaust and f_d and f_w are the fractions of the total available energy in the dry and wet regions, respectively.

The efficiency of pumps is assumed to be 0.75 and the overall efficiency of turbines used to drive the pumps is assumed to be 0.75. Efficiency of the electrical generator is assumed to be 0.985.

B.7.6.2 Cavity Conditions

p press water	170	130	100	80
p cav, min	340	260	200	160
T cav, min	470	470	470	470
p cav, avg	374	286	220	176
T cav, avg	520	520	520	520
p cav, max	408	312	240	192
T cav, max	570	570	570	570

Temperature of minimum-temperature minimum-pressure cavity steam after throttling to pressurized water pressure:

T throt, min	400	410	425	435

Reference 2 is used for all thermodynamic properties.

Depth of the cavity is based on having p cav, max equal to 75 percent of the overburden pressure. Density of the overburden is 2.25 g/cm^3

Depth, L, km	2.48	1.89	1.45	1.16

B.7.6.3 Pressurized Water Conditions

p press water	170	130	100	80
T sat at p	352	331	311	295
T liq, max	342	321	301	285
T liq, avg	332	311	291	275
T liq, min	322	301	281	265

B.7.6.4 Turbine Steam Conditions

Saturated steam temperature is 40°C less than T liq, avg.

p press water	170	130	100	80
T sat, tb	292	271	251	235
p sat, tb	76.6	55.9	40.4	30.6

Superheated steam has pressure (p sat, tb) and temperature 50°C less than (T throt, min)

T sup, tb	350	360	370	380

B.7.6.5 Power to Return Liquid to Cavity

p press water	170	130	100	80
T liq, min	322	301	281	265
v liq, min	1.46	1.39	1.32	1.28
h liq, min	1460	1368	1238	1160
h cav, avg	3051	3184	3276	3333

The difference between these enthalpies is the heat given up in the heat exchanger

Δh	1591	1816	2038	2173

Assuming an overall terminal efficiency of 0.30 the mass flow rate, g/sec, for 2000 MW output can be obtained.

$\dot{M}$	4.20×10^6	3.69×10^6	3.29×10^6	3.08×10^6

The pressure rise required of the liquid injection pump is assumed equal to the difference between (p cav, avg) and (p press water) plus pipe friction loss and less gravity pressure. The pipe friction loss is assumed equal to (p press water) in order to reduce the pipe requirements which tend to become excessive.

p press water	170	130	100	80
p cav, avg -p press water	204	156	120	96
Δp friction	170	130	100	80
Δp gravity	166	133	108	89
Δp pump, avg	208	153	112	87
pump output, avg, MW	128	79	49	35

Pump input power expressed as a percentage of the 2000 MW terminal output power, assuming a pump efficiency of 0.75, is as follows

Pump input, percent	8.4	5.2	3.2	2.3

The cavity pump factor for pump loss is

cpf	.922	.950	.968	.977

B.7.6.6 Rankine Cycle, Saturated Steam

e (Rankine)	.373	.361	.348	.335

The Rankine cycle efficiency is corrected for condensate pumping power using .75 for the pump efficiency and .75 for the driving turbine efficiency.

e(Rankine, cor)	.368	.358	.346	.333
x ideal	.675	.695	.715	.729
x corrected for reheat	.735	.754	.772	.784
mcf	.909	.914	.918	.921
cpf	.922	.950	.968	.977
Turbine factor .95 x .87	.827	---	---	---
Generator factor	.985	---	---	---
e(Rankine, term)	.251	.254	.250	.244

B.7.6.7 Regenerative Cycle, Saturated Steam

The temperature to which the condensate is heated by continuous regenerative extraction is assumed to be

$$T\ \text{regen} = (T\ \text{sat tb} - T\ \text{cond}) \times 0.75 + T\ \text{cond}$$

where T cond is the temperature in the condenser and is equal to 39°C.

T regen	229	213	198	186
e(regen, sat)	.445	.424	.400	.381

The basic cycle efficiency is corrected for condensate pumping power using .75 for the pump efficiency and .75 for the driving turbine efficiency.

e(regen, sat, cor)	.439	.419	.398	.379

All other correction factors are the same as those used for the Rankine cycle.

e(regen, sat, term)	.299	.297	.288	.278

B.7.6.8 Regenerative Cycle, Superheated Steam

T sup, tb	350	360	370	380
T sat, tb	292	271	251	235
p sat, tb	76.6	55.9	40.4	30.6
T regen	229	213	198	186
x ideal	.725	.760	.790	.814
x corrected for reheat	.793	.828	.857	.881
mcf	.924	.932	.940	.945
e(regen, sup)	.449	.430	.411	.395

The basic efficiency is corrected for pump efficiency (.75) and turbine efficiency (.75)

e(regen, sup, cor)	.443	.426	.409	.393
e(regen, sup, term)	.300	.308	.305	.295

SYMBOLS

T	Temperature, C, unless specified K
ΔT	Temperature difference, C
s	Entropy, j/g-K
e	Efficiency
h	Enthalpy, j/g
Δh	Enthalpy difference, j/g
p	Pressure, bars
Δp	Pressure difference, bars
$\dot{M}$	Cavity steam mass flow rate, g/sec
v	Specific volume, cm^3/g
x	Quality of steam
y	Quality of steam, corrected
L	Depth, km

ABBREVIATIONS

mcf	Moisture correction factor
cpf	Cavity pump factor
sup	Super heat
sat	Saturation
cav	Cavity
tb	Turbine
term	Terminal (electrical)
regen	Regenerative
press	Pressurized
liq	Liquid
avg	Average
max	Maximum
min	Minimum
throt	Throttled
cor	Corrected

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B.8 VARIATION OF PACER HIGH PRESSURE PIPES WITH CAVITY PRESSURE

(L. Gore)

B.8.1 Introduction

In Section B.7, Pacer Thermal Efficiency, the performance of pressurized water systems was analyzed for four different cavity pressures, 160, 200, 260 and 340 bars. It was concluded that if power for pumping the liquid back into the cavity is included in the system losses, there is very little variation of overall thermal efficiency with cavity pressure or depth. Design of pipes for different cavity pressures and depths is not considered in

In Section B.4, the design of pipes for a pressurized water system operating at an average cavity pressure of 320 bars was investigated.

The object of this report is to present the results of a design study of the pipes for the four cavity pressure conditions analyzed in Section B.7 i.e., maximum pressures of 192, 240,312 and 408 bars.

B.8.2 Assumptions

Temperature in the cavity

average 520°C
minimum 470°C
maximum 570°C

Pressure in the cavity

minimum is twice the pressurized water pressure
maximum is 20 percent greater than the minimum
maximum is 75 and 100 percent of overburden pressure.

The rate of flow of cavity steam is based on 2000 MW electrical output obtained at an overall thermal efficiency of 0.30. The temperature of the liquid returned to the cavity by the pump is assumed to be 30°C less than the saturation temperature corresponding to the pressurized water pressure.

At minimum cavity pressure and temperature the pipes are designed for the following friction pressure losses with a flow corresponding to 2000 MW output

steam pipe -- pressurized water pressure less the
steam gravity pressure
liquid pipe -- pressurized water pressure

Two values for absolute roughness of the steam pipe wall are assumed [1].

0.00015 ft -- commercial steel pipe
0.001 ft -- smooth concrete pipe

The liquid pipe was assumed to have an absolute roughness of 0.00015 ft. Maximum pipe wall thickness is limited to 2 inches because it is likely the pipes will be made of corrosion resisting material similar to stainless steel or Inconel.

The allowable pipe wall stress of 13,100 lb/in^2 is based on 18% Cr-8% Ni stainless steel at 1050°F (566°C) as specified by the ASME Standard Code for Pressure Piping [1]. The corresponding diameter is determined by the formula specified by the ASME Code, using the maximum pressure in the cavity.

15$/kg was assumed for the cost of the pipe, including fabrication costs at the site. Costs for drilling the holes and grouting the pipe in place have not been included. These costs could vary from \$100,000 to \$350,000 per pipe depending upon many factors which are unknown at the present time. In Reference 2, 15 \$/kg was used for estimating the cost of stainless steel components for various fusion power systems. In References 3 and 4 costs are given for 4 inch stainless steel pipe. These range from 6 to 8 \$/kg for the 1973 costs of Reference 3 to 16 to 20 \$/kg for the projected 1974 costs of Reference 4.

B.8.3 Results

Results of the calculations in terms of size, number, mass and cost of the pipes are shown in the following tabulation as a function of cavity pressure. Results are combined values for steam (up) and liquid (down) pipes.

Cavity steam pressure				
maximum, bars	408	312	240	192
minimum, bars	340	260	200	160
Pressurized water pressure, bars	170	130	100	80
Pipe inside diameter, cm	14	20	29	38

CAVITY MAXIMUM PRESSURE = OVERBURDEN PRESSURE

Depth, km	1.86	1.42	1.09	0.87
Number of pipes	135	45	19	8.1
Mass of pipes, kg	62×10^6	22×10^6	9×10^6	4.1×10^6
Cost at 15 \$/kg, dollars	930×10^6	330×10^6	135×10^6	62×10^6

CAVITY MAXIMUM PRESSURE = 0.75 x OVERBURDEN PRESSURE

Depth, km	2.48	1.89	1.45	1.16
Number of pipes	155	52	22	9.3
Mass of pipes, kg	96×10^6	34×10^6	14×10^6	6.3×10^6
Cost at 15 \$/kg,dollars	1440×10^6	510×10^6	210×10^6	95×10^6

CAVITY MAXIMUM PRESSURE = 0.75 x OVERBURDEN PRESSURE
(Pressurized Water Pressure = 80 Bars)

Number of pipes	139	48	21	9.3
Mass of pipes, kg	86×10^6	31×10^6	14×10^6	6.3×10^6
Cost at 15 \$/kg, dollars	1290×10^6	470×10^6	210×10^6	95×10^6

Steam pipes have smooth concrete roughness and liquid pipes have commercial steel roughness.

B.8.4 Discussion

The main reason for the increase in pipe cost is the higher price of the pipe material. The nominal value of 2.2 \$/kg used in Section B.4 has been increased to 15 \$/kg, [2,3,4].

Pipe walls are designed to withstand maximum cavity pressure. This means relatively thick pipe walls and use of the ASME Code for Pressure Piping makes it difficult to obtain simple scaling laws.

If the thin pipe formula is assumed for simplicity,

$$s = \frac{pd}{2t}$$

where

s = wall stress
p = pressure
t = wall thickness
d = inside diameter

The volume of pipe material per unit length of pipe is

$$v_p = \pi dt$$

The following equation from Reference 1 is adequate for pressure drop in the pipe due to friction. It is based on the assumption of a perfect gas, isothermal conditions and a constant wall friction factor

$$p_1^2 - p_2^2 = 4f \frac{L}{d} RT \frac{\dot{M}^2}{A^2}$$

where

p_1 = cavity pressure
p_2 = pressurized water pressure
f = friction factor
L = length of pipe (depth)
R = gas constant
T = gas temperature
$\dot{M}$ = mass flow rate
A = pipe flow area

Cavity pressure and pipe length are related by

$$p_1 = \alpha \rho_o g L$$

where

α = ratio cavity maximum pressure to overburden pressure
ρ_o = density of overburden
g = gravitational constant

In terms of the pipe wall thickness t, the total volume of pipe material is

$$V_p = \frac{p_1^2}{(1 - p_2^2/p_1^2)^{1/2}} \frac{2}{s\alpha\rho_o g} \left(\frac{2RTf\dot{M}^2}{ts\alpha\rho_o g}\right)^{1/2}$$

and in terms of the number of pipes, n, the volume is

$$V_p = \frac{n^{1/5} p_1^{8/5}}{(1 - p_2^2/p_1^2)^{2/5}} \frac{2}{2s\alpha\rho_o g} \left(\frac{64RTf\dot{M}^2}{\pi^2 \alpha\rho_o g} \right)^{2/5}$$

For example, if the 5 cm thick walls used for the calculations in this report could be increased to 10 cm the volume of the pipe material would be reduced to about 70 percent of the 5 cm thick pipe volume. Similarly, if instead of 100 pipes only one larger pipe could be used, its volume of material would be reduced by a factor of $100^{-1/5}$ or to about 40 percent of the 100 pipe volume.

The value of V_p predicted by the above method may be low by a factor of two when compared to pipes satisfying the ASME code. Correction for change of mass flow rate with p_1 and p_2 for constant power output (2000 mw) must be made. The mass flow rate increases with increase in p_1 and p_2. Correction must also be made for increases in f as d becomes smaller with increasing pressure.

B.8.5 Analysis

Pressures and Temperatures

p pressurized water, bars	170	130	100	80
T return liquid, °C	322	301	281	265
p cavity, max, bars	408	312	240	192
avg, bars				
min, bars	340	260	200	160
T cav, max, °C	570			
avg, °C	520			
min, °C	470			
L(α = 0.75), km	2.48	1.89	1.45	1.16
L(α = 1.00), km	1.86	1.42	1.09	0.87

Pipe Diameter

$$t = \frac{pD}{2s + yp} + C$$

t = wall thickness, 5.08 cm (2.0 in)

C = 0.165 cm (0.065 in)

D = outside diameter

s = allowable stress, 904 bars (13,100 lb/in^2)

y = 0.4

p cav, max, bars	408	312	240	192
D cm	23.9	30.5	38.6	48.3
d cm	13.7	20.3	28.5	38.1
$L(\alpha = 0.75)/d$	18100	9300	5100	3040
$L(\alpha = 1.00)/d$	13600	6970	3920	2280
$\pi d^2/4$, cm^2	148	323	638	1140
$(D^2-d^2)\pi/4$, cm^2	299	407	532	700
Mass per unit length, (ρ = 8.3), kg/cm	2.48	3.38	4.41	5.80
Mass of one pipe (α = 0.75), kg	615×10^3	640×10^3	640×10^3	673×10^3
(α = 1.00), kg	461×10^3	480×10^3	480×10^3	505×10^3

Average Specific Volume

Steam

v cav, min, cm^3/g	6.17	9.46	13.57	17.97

At the top end of the pipe the pressure is equal to the pressurized water pressure and the enthalpy is equal to the enthalpy in the cavity less the equivalent of the work performed against gravity in lifting the unit mass to the surface.

h cav, min, j/g	2848	3022	3135	3203
$gL \times 10^{-7}$, j/g	24	19	14	11

h top, min, j/g	2824	3003	3121	3192
T top, min, °C	383	393	408	420
v top, min, cm^3/g	11.9	18.6	26.9	35.9

$\bar{v} = 2(v\ cav)(v\ top)/(v\ cav - v\ top)$

$\bar{v}$, cm^3/g	8.15	12.60	18.05	24.00

Liquid

The returning liquid leaves the pressurized water heat exchanger at approximately 30°C less than the saturation temperature corresponding to the pressurized water pressure.

T liq, return °C	322	301	281	265
$\bar{v}$ liq, return, cm^3/g	1.385	1.350	1.297	1.280

Steam Flow Rate

For minimum cavity pressure and temperature

h top, min, j/g	2824	3003	3121	3192
h return liq, j/g	1460	1368	1238	1160
Δh heat removed, j/g	1365	1365	1883	2032
$\dot{M}$, kg/sec	4890	4080	3640	3280

The steam flow rate is based on 2000 Mw electrical output at a thermal efficiency of 0.30, Section B.7. Values for (h top, min) are for depth L(α = 0.75). They are also used for depth L(α = 1.00) as the correction for depth is negligible.

Reynolds Numbers and Friction Factors

Steam

L(α = 0.75), km	2.48	1.89	1.45	1.16
G g/cm^2-sec (estimated)	280	320	320	340
$\bar{\mu}$ Micropoise	309	292	280	279
$(Gd/\bar{\mu})$	12.4×10^6	22.3×10^6	32.6×10^6	47.4×10^6
$(0.00015 \times 30.5/d) \times 10^3$	0.334	0.225	0.161	0.120
4f Commercial steel	0.015	0.014	0.013	0.012
4fL/d Commercial steel	272	130	66.5	36.5
$(0.001 \times 30.5/d \times 10^3$	2.22	1.50	1.07	0.80
4f Smooth concrete	0.024	0.022	0.020	0.018
4fL/d Smooth concrete	435	204	102	54.8

Liquid

G g/cm^2-sec (estimated)	680	980	1200	1470
$\bar{\mu}$ Micropoise	850	930	1040	1070
(Gd/μ)	11.0×10^6	21.4×10^6	32.8×10^6	52.1×10^6
4f Commercial Steel	0.015	0.014	0.013	0.012
4fL/d Commercial steel	272	130	66.5	36.5

Values of $\bar{\mu}$ are from Reference 2, values for 4f are from Reference 1. For values of Reynolds number (Gd/μ) above about 10^7 the flow is completely turbulent in commercial steel and smooth concrete pipes and the friction factor depends only upon the surface roughness.

Pipe Flow

Steam

The design condition for the pipes occurs at minimum cavity pressure and temperature and it is assumed that for this condition the cavity pressure is twice the pressurized water pressure.

Gravity pressure, $(gL/\bar{v}) \times 10^{-6}$, bars	29.8	14.7	7.9	4.8
Δp friction, bars	140	115	92	75

$(\Delta p \text{ friction}) = (4fL/d)(G^2\bar{v}/2)$

Commercial steel pipe roughness

$G^2\bar{v}/2$, bars	0.515	0.885	1.383	2.055
G^2	128×10^3	141×10^3	153×10^3	171×10^3
G, g/cm^2-sec	358	375	391	414
Flow area, cm^2	13920	10900	9300	7930
Number of pipes	94.0	33.8	14.6	6.95
Mass of pipes, kg	57.8×10^6	21.6×10^6	9.35×10^6	4.68×10^6

Smooth concrete pipe roughness

$G^2\bar{v}/2$, bars	0.322	0.565	0.902	1.370
$G^2 \times 10^6$	80×10^3	90×10^3	100×10^3	114×10^3
G, g/cm^2-sec	282	300	316	370
Flow area, cm^2	17700	13600	11500	8850
Number of pipes	120	4200	18.1	7.75
Mass of pipes, kg	74.0×10^6	26.8×10^6	11.6×10^6	5.21×10^6

Liquid

Gravity pressure, $gL/\bar{v}$, bars	176	137	109	89
Δp friction, bars	170	130	100	80
Δp pump, bars	164	123	100	71

The friction loss is assumed to equal the difference between minimum cavity pressure and the pressurized water pressure.

Commercial steel pipe roughness

$G^2\bar{v}/2$, bars	0.625	1.000	1.500	2.190
G^2	902×10^3	1480×10^3	2315×10^3	3420×10^3
G, g/cm^2-sec	950	1217	1522	1850
Flow area, cm^2	5250	3350	2390	1770
Number of pipes	35.5	10.4	3.74	1.55
Mass of pipes, kg	21.8×10^6	6.65×10^6	2.39×10^6	1.04×10^6
Pump output power, MW	134	82	57	37

The values for pump power are rough estimates of the average pump power. The above value of Δp for the pump was increased by 10 percent of the cavity minimum pressure to account for discharge at the average cavity pressure. The mass flow rate for minimum cavity pressure and temperature was used instead of the mass flow rate for average cavity conditions.

Total Pipes

Commercial steel pipe roughness, steam and liquid

Number	129.5	44.2	18.34	8.50
Mass, kg	79.6×10^6	28.25×10^6	11.74×10^6	5.72×10^6

Smooth concrete pipe roughness, steam; commercial steel pipe roughness, liquid

Number	155.5	52.4	21.74	9.30
Mass, kg	95.8×10^6	33.45×10^6	13.99×10^6	6.25×10^6

SYMBOLS

p	pressure
Δp	pressure difference
T	temperature
L	depth
α	ratio, cavity maximum pressure to overburden pressure
d	pipe inside diameter
D	pipe outside diameter
v	specific volume
$\bar{v}$	average v
h	enthalpy
Δh	enthalpy difference
$\dot{M}$	steam mass flow rate
s	Steam mass flow rate per unit pipe area
$\bar{\mu}$	average viscosity
f	Friction factor for pipe flow
g	Gravitational constant
ρ	Mass density

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B.9 ATTENUATION OF WEAK SHOCK WAVES IN PIPES (E. Martinelli, L. Gore)

The time variations of static overpressure at the cavity wall during energy addition is illustrated in Figure 1. The cavity operating pressure is about 300 bars.

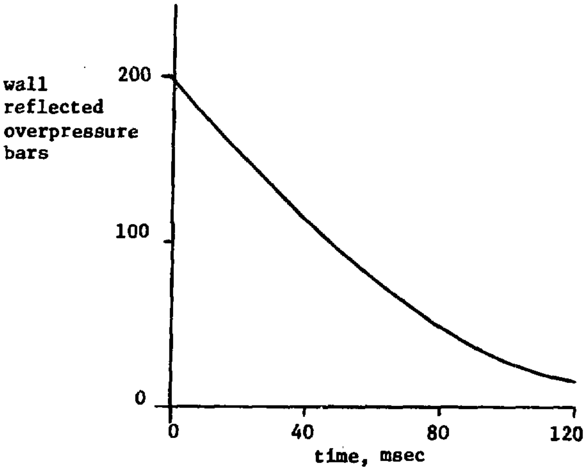

Figure 1. Static Overpressure at Cavity Wall

Since the pipe flow area is very small compared to the cavity surface area and to the thickness of the overpressure pulse, it can be assumed that the pulse of Figure 1 is applied to the open ends of the pipes. As a result, overpressure waves of sufficient magnitude to damage the pipes and other equipment may be transmitted along the pipes.

It is the object of this report to present the results of a preliminary investigation of the transmission and attenuation of these waves.

In order to simplify the analysis we assume the pulse of Figure 1 can be represented by a rectangular sonic pulse of duration Δt_o and amplitude Δp_o. We assume that fluid is flowing in the pipe with velocity V before application of the pressure pulse. Referring to Figure 2, as the pulse travels through the fluid in the pipe, the front and back are assumed to have velocity V + c relative to the pipe wall.

c = velocity of sound

Between the front and back of the pulse the velocity of the fluid relative to the pipe is V + u where

$$u = \frac{\Delta p}{\rho c}$$

Δp = instantaneous overpressure in the pulse

ρ = density of fluid.

The length of the pulse remains constant* and is equal to

$$x_o = \Delta t_o c$$

Generally, for flow rates of practical significance, the flow through the pipe at velocity U will be fully developed turbulent flow. This is determined by the Reynolds number

$$Re = \frac{\rho U d}{\mu}$$

where

d = pipe diameter

μ = viscosity

---

*Reduction in amplitude of the pulse due to an increase in length and duration as it travels along the pipe is not considered.

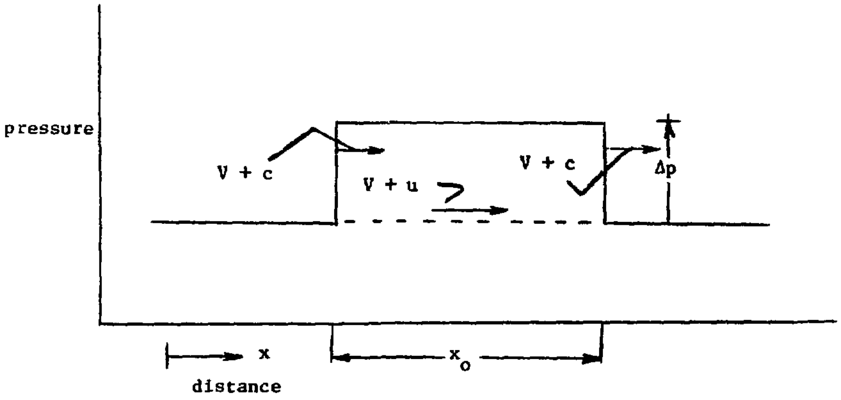

Figure 2. Rectangular Pulse

Typical values of Re range from 10^7 to 10^8 and in this range the friction factor used to express the shear friction stress on the wall is practically independent of the Reynolds number.

$$s = f \frac{\rho V^2}{2}$$

f = friction factor

s = shear stress

Using this concept of friction the total drag force acting on the fluid within the traveling pulse is at any instant

$$\pi d x_o f \rho \frac{(V + u)^2}{2} \quad .$$

The fluid within the pulse would normally be subjected to a force

$$\pi d x_o f \frac{\rho}{2} V^2$$

which is balanced by the steady flow friction pressure gradient along the pipe. Thus, the net force acting on the pulse which reduces the momentum of the fluid in the pulse is

$$\pi d x_o f \frac{\rho}{2} [(V + u)^2 - V^2]$$

or

$$\pi d x_o f \frac{\rho}{2} (2uV + u^2)$$

At any time t the momentum of the fluid between the two faces of the pulse is

$$\frac{\pi}{4} d^2 x_o \rho (V + u)$$

and the time rate of change, since V is constant, is

$$\frac{\pi}{4} d^2 x_o \rho \frac{du}{dt}$$

Thus, for the net force equilibrium of the fluid in the pulse we have

$$- \pi d x_o f \frac{\rho}{2} (2uV + u^2) - \frac{\pi}{4} d^2 x_o \rho \frac{du}{dt} = 0$$

or

$$\frac{du}{dt} = - \frac{2f}{d} (2uV + u^2)$$

The solution is

$$\frac{u}{u_o} = \frac{\Delta p}{\Delta p_o} = \frac{(2V/u_o)\exp(-4fVt/d)}{1 + (2V/u_o) - \exp(-4fVt/d)}$$

where

$$u_o = \frac{\Delta p_o}{pc}$$

$$t = \frac{L}{V+c} \sim \frac{L}{c}$$

L = pipe length

The exponent can be expressed in terms of the pipe length to diameter ratio

$$\frac{4fVt}{d} \sim 4f \frac{L}{d} \frac{V}{c}$$

For the case where $V << u_o$ the solution is

$$\frac{u}{u_o} = \frac{\Delta p}{\Delta p_o} \quad \frac{1}{1+2fu_o t/d}$$

The following calculations indicate the magnitude of the factors involved for a cavity filled with steam operating at an average pressure of 320 bars and temperature of 525°C.

$d = 30$ cm
$\rho = .115$ g/cm^3
$V = 50$ m/sec
$\mu = 340 \times 10^{-6}$ poise

$$Re = \frac{.115 \times 5000 \times 30}{340 \times 10^{-6}} = 5.1 \times 10^{7}$$

$f \sim 0.003$

$L = 1.45$ km
$c = 600$ m/sec
$t = 1450/650 = 2.2$ sec

The following illustrate the results for two values of Δp_o and three values of V.

Δp_o, bars	100	200
u_o, m/sec	145	290
V, m/sec	50	50
$2V/u_o$	0.690	0.345
2fVt/R	4.4	
exp(-2fVt/R)	0.012	
$\Delta p/\Delta p_o$	0.0049	0.0031
V, m/sec	10	10
$2V/u_o$	0.138	0.069
2fVt/R	0.88	
exp(-2fVt/R)	0.486	
$\Delta p/\Delta p_o$	0.1030	0.0575
V, m/sec	0	0
$\Delta p/\Delta p_o$	0.1355	0.0722

It is concluded that the steady flow velocity of the steam has a significant effect on the attenuation. At 50 m/sec the pulse is highly attenuated and becomes insignificant; however, for zero flow velocity the attenuation is considerably less and probably requires that engineering provision must be made to absorb the surges in pressure, or periods of energy addition must be limited to periods of full steam flow.

In the case of the pipes returning liquid water to the cavity the velocity V is nearly zero and the attenuation is very low as illustrated in the following table.

Δp_o, bars	100	200
c, liquid ~250°C m/sec	900	
p, g/cm^3	0.8	
u_o, m/sec	14	28
f	0.003	
t, sec	1.6	
d, cm	30	
$2fu_ot/d$	0.45	0.90
$\frac{u}{u_o} \sim \frac{\Delta p}{\Delta p_o}$	0.69	0.53

It is concluded that provision must be made to absorb the surges in pressure.

B.10 PIPES, HEAT EXCHANGERS AND COMPRESSORS FOR A PACER SYSTEM USING AIR AS THE PRIMARY FLUID (L. Gore)

B.10.1 Summary

The preliminary design aspects of the pipes, heat exchangers and compressors for a PACER system using air as the cavity fluid are examined. The pipes are designed to bring the hot air from the cavity to the surface where it is used to generate steam in a heat exchanger before it is returned to the cavity by a compressor. Calculations are performed for cavity pressures of 100, 200 and 300 bars. The average cavity operating temperature is 520°C. Results for a 2000 MW output power plant operating at a cavity pressure of 200 bars and using about 1000 MW to drive the compressor are shown in the following tabulation. It is concluded that 1) cost of the pipes is extremely large, 2) overall thermal conversion efficiency is poor, and 3) the number of pipes is impossible.

Cavity Pressure 200 Bars,
2900 lb/in^2 Depth 0.9 km, 3000 ft, 2000 MW output

	Stainless Steel	Cr-Mo Steel
"Up" pipes, $	900×10^6	720×10^6
"Down" pipes, $	610×10^6	135×10^6
Compressors, $	40×10^6	70×10^6
Heat exchangers, $	22×10^6	22×10^6
Compressor power, MW	1000	1000
Overall thermal efficiency, percent	23	23
Number of pipes, "up"	100	80
, "down"	83	67
Pipe cost, $/lb	7.00	2.50
Pipe wall thickness, in	2	8
Pipe diameter, up, in	18	30
, down, in	21	83

B.10.2 System

If a gas such as air is to be used as the working fluid, there are two general systems which can be used to generate power. One system is based on a gas turbine type cycle and was analyzed in Section B.7. It is a simple system; but, it has the disadvantage of a thermal efficiency which is probably less than 15 percent. The other system uses the hot gas from the cavity to generate steam in a heat exchanger. The cavity gas leaving the heat exchanger is returned to the cavity by a compressor and the steam which is generated is used to drive a steam turbine. Figure 1 shows a system of this type.

B.10.3 Operating Conditions

Experience gained from analysis of other systems and components (Sections B.3, B.4, B.8) indicate that the cost of the "up" and "down" pipes in Figure 1 will be the overwhelming factor in design of the system. This means that T_2, the temperature of the gas leaving the heat exchanger, must be made as low as possible so that the mass rate of gas flow in the pipes will be minimized. But, T_2 is fixed by the minimum temperature occurring in the steam boiler, i.e., T_2 should be about 50°F higher than the saturation temperature of the water in the boiler in order to achieve heat transfer. In Section B.7, it was shown that about the minimum saturation temperature that could be used was 482°F (250°C). The corresponding overall thermal efficiency was about 30 percent. Thus, T_2 should be about 532°F.

B.10.4 Mass Flow Rate and Compressor Power

Assuming the gas has a constant specific heat, c_p, the heat removed from a unit mass of gas in the heat exchanger is

$$c_p(T_1 - T_2)$$

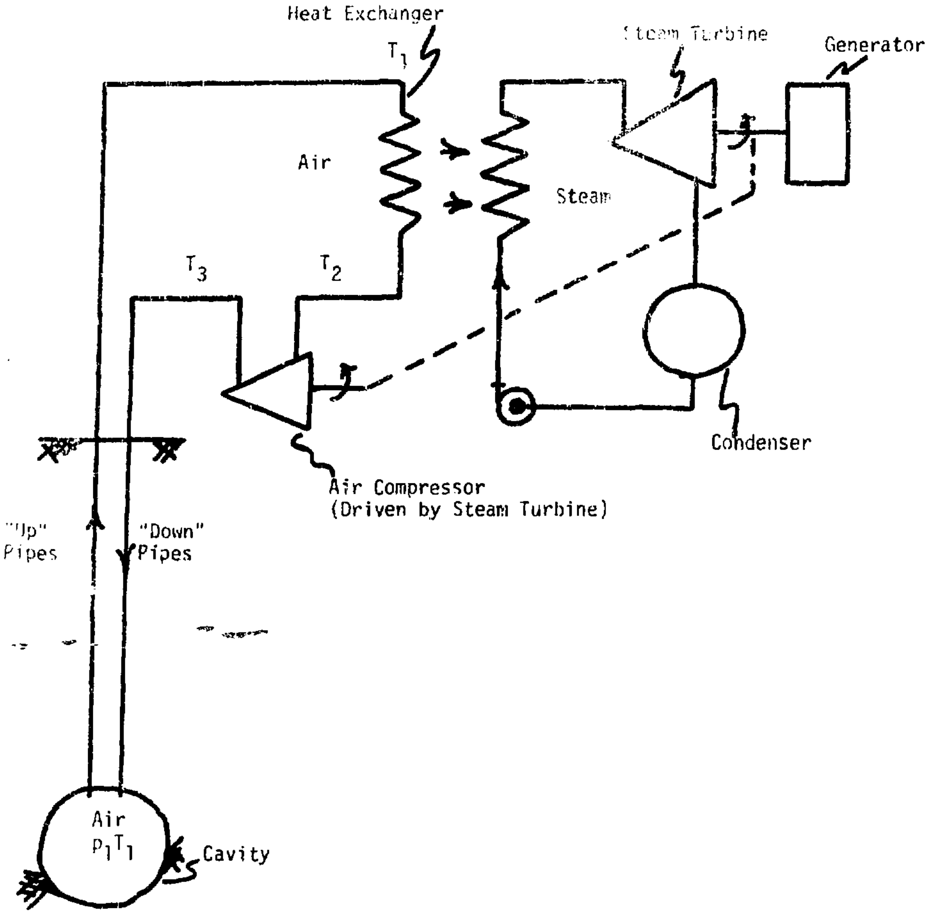

Figure 1. System Using Air as Primary Fluid

If e_t is the overall thermal conversion efficiency of the steam turbine cycle the work performed by the turbine is

$$c_p(T_1 - T_2)e_t$$

Part of the turbine work must be used to drive the compressor. The work absorbed by the compressor is

$$c_pT_2(X^{(\gamma-1)/\gamma}-1)/e_c$$

where X is the pressure ratio, γ is the ratio of specific heats and e_c is the efficiency of the compressor. The pressure ratio depends upon the friction pressure losses in the "up" and "down" pipes and in the heat exchanger and upon the gravity pressure increments in the "up" and "down" pipes.

$$X = \frac{p_1 + \delta_d p_1 - \bar{\rho}_d gL}{p_1 - \delta_u p_1 - \delta_{hx} p_1 - \bar{\rho}_u gL}$$

p_1 = pressure in cavity

$\delta_u p_1$ = friction pressure loss in "up" pipes

$\delta_d p_1$ = friction pressure loss in "down" pipes

$\delta_{hx} p_1$ = friction pressure loss in heat exchanger

$\bar{\rho}_u gL$ = gravity pressure increment in "up" pipe

$\bar{\rho}_d gL$ = gravity pressure increment in "down" pipe

ρ = average mass density of gas in pipe

g = gravity constant

L = length of pipe

$$X = \frac{1 + \delta_d - \bar{\rho}_d gL/p_1}{1 - \delta_u - \delta_{hx} - \bar{\rho}_u gL/p_1}$$

Values for the gravity pressure factors are shown in the following tabulation assuming the gas is air and that the cavity pressure equals the overburden pressure.

ρ_{ob} = 2.25 g/cm^3 (w_{ob} = 0.08 lb/in^3)

p_1, bars	100	200	300
, lb/in^2	1450	2900	4350
L, km	.455	.910	1.36
, ft	1490	3000	4450
T_1, R	1428	1428	1428
$T_3 \sim T_2$, R	992	992	992
$(\rho_d - \rho_u)gL/p_1$	0.0087	0.0174	0.0262

Experience (see B.3, B.4) with systems similar to the systems of Figure 1 indicates that for compressor power less than one-half of the output power, the values of δ_u, δ_{hx} and δ_d will be small relative to unity, i.e., less than 0.05. Since the gravity terms are also small the equation for X can be written with negligible error as

$$X = 1 + \delta - (\bar{\rho}_d - \bar{\rho}_u)gL/p_1$$

where

$$\delta = \delta_u + \delta_{hx} + \delta_d$$

using the notation

$$Y = X^{(\gamma-1)/\gamma} - 1$$

the useful work output of the system per unit mass of gas is

$$c_p(T_1 - T_2)e_t - c_pT_2Y/e_c$$

and the corresponding heat removed is

$$c_p(T_1 - T_2) - c_pT_2Y/e_c$$

so that the thermal efficiency of the system as far as useful output is concerned is

$$e_o = \frac{(1 - T_2/T_1)e_t - (T_2/T_1)Y/e_c}{(1 - T_2/T_1) - (T_2/T_1)Y/e_c}$$

The ratio of compressor power to useful output power is

$$\frac{P_c}{P_o} = \frac{(T_2/T_1)Y/e_c}{(1 - T_2/T_1)e_t - (T_2/T_1)Y/e_c}$$

The mass flow rate for an output power P_o is

$$\dot{W} = \frac{P_o}{c_p T_1[(1 - T_2/T_1)e_t - (T_2/T_1)Y/e_c]}$$

Values for e_o, P_c/P_o and $\dot{W}$ are listed in the subsequent tabulations for various values of δ and p_1.

B.10.5 Pipe Design, Weight and Cost

The following equation [1] can be used for the relation between the flow rate and friction pressure loss. The effects of gravity pressure drop on density have been neglected and the symbols used are those for the "up" pipe.

$$p_1^2 - p_2^2 = 4f\frac{L}{d}\,\frac{RT_1}{g}\,\frac{\dot{W}^2}{A_u^2}$$

d = diameter, inside

A_u = total area for flow

f = friction factor

Isothermal flow is assumed at temperature T_1 and it is assumed that 4fL/d is very large compared to entrance, exit and other fixed losses. Since the friction pressure drop is $\delta_u p_1$ for the "up" pipe

$$p_1^2 - p_2^2 = p_1^2\,[1 - (1-\delta_u)^2]$$

and as the largest value of δ_u being considered is 0.05 it is permissible to use the approximation

$$p_1^2 - p_2^2 = 2\delta_u p_1^2$$

After making this substitution the expression for total flow area A_u is

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[1] Mechanical Engineers Handbook, Marks, Ed. 6, 1964, McGraw-Hill

$$A_u = \left[4f \frac{L}{d} \frac{RT_1}{g} \frac{\dot{W}^2}{2\delta_u \, p_1^{\,2}}\right]^{1/2}$$

Pipes for PACER systems should be designed in accordance with the ASME Code for Pressure Piping, [1] if possible. But, the equations from the Code add complications which are undesirable algebraically and it is assumed, for simplicity, that the following thin pipe wall equations are adequate for the first iteration.

$$t = \frac{pd}{2s} \qquad\qquad \frac{t}{d} = \frac{p}{2s}$$

$$\frac{\pi}{4}\left(D^2 - d^2\right) \sim \frac{\pi}{4} d^2 \left(4\frac{t}{d}\right)$$

where

p = pressure
d = diameter, inside
D = diameter, outside
t = wall thickness
s = stress

Assuming that the thickness of the pipe wall is limited by manufacturing considerations, the volume of metal in the "up" pipes is

$$V_u = \frac{2p_1^{\,2}}{sw_{ob}} \left[\frac{4f}{w_{ob}} \frac{RT_1}{2tsg} \frac{\dot{W}^2}{2\delta_u}\right]^{1/2}$$

The number of pipes is

$$n_u = \frac{4}{\pi d^2} \left[\frac{4f}{w_{ob}} \frac{RT_1}{2tsg} \frac{\dot{W}^2}{2\delta_u}\right]^{1/2}$$

If the limitation on t is removed and a single pipe is assumed

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[1] *Mechanical Engineers Handbook*, Marks, Ed. 6, 1964, McGraw-Hill.

$$d^5 = \frac{16}{\pi^2} \frac{4f}{w_{ob}} \frac{RT_1}{gp_1} \frac{\dot{W}^2}{2\delta_u}$$

$$V_u = \frac{\pi}{2} \frac{p_1^{\,2}}{s w_{ob}} \left[\frac{16}{\pi^2} \frac{4f}{w_o} \frac{RT_1}{gp_1} \frac{\dot{W}^2}{2\delta_u} \right]^{2/5}$$

B.10.6 Pipe Calculations

Calculations for "up" pipes have been performed for the following conditions:

Stainless steel

T_1 = 1428 R

T_2 = 992 R

$T_3 = T_2$ approximately

e_t = 0.30

e_c = 0.85

s_u = 13100 lb/in^2

s_d = 15000 lb/in^2

w_{ob} = 0.08 lb/in^3

w_p = 0.30 lb/in^3

cost = $7.00/lb

f = 0.004

$\delta_u = \delta/3$

$\delta_d = \delta/3$

The weight and cost of the multiple stainless steel "down" pipes can be obtained by multiplying the weight of the "up" pipes by 0.68. Calculations for single pipes for minimum and maximum values of δ have been included to illustrate the cost reduction potentially available with single pipes.

If Cr-Mo pipe is assumed the following values for stress and cost can be used

$$s_u = 5500 \text{ lb/in}^2$$

$$s_d = 15{,}000 \text{ lb/in}^2$$

$$\text{cost} = 2.50 \text{ \$/lb}$$

Assuming that the thickness can be increased to 8.0 in. the multipliers to be used on the multiple stainless steel "up" pipe weight and cost to obtain the weight and cost of Cr-Mo pipes are 0.80 for the "up" pipes and 0.15 for the "down" pipes.

UP PIPES - Stainless Steel

$p = 1450\ lb/in^2$ (100 bars)

Multiple pipes $d = 36.0$ in $t = 2.0$ in

δ	.0087	.0300	.0500	.1000	.1500
$(\rho_d - \rho_u)gL/p_1$	.0087	.0087	.0087	.0087	.0087
$X - 1$	0	.0213	.0413	.0913	.1413
Y	0	.0060	.0116	.0253	.0384
$\Delta T - \Delta T_c$, R	436	429	422	406	391
ΔT_c, R	0	7	14	30	45
ΔT_t, R	131				
$\Delta T_t - \Delta T_c$, R	131	124	117	101	86
$\dot{W}$, lb/sec	10^3 x 60.5	x 63.8	x 67.7	x 78.5	x 92.0
F_c/P_o	0	.0565	.1197	.2970	.523
J	10^3 x 4.0				
K	.116				
$\delta^{1/2}$	.0932	.173	.224	.316	.387
V, in^3	10^6 x 301	x 171	x 140	x 115	x 110
W, lb	10^6 x 90.5	x 51.3	x 42.0	x 34.5	x 33.0
C, $	10^6 x 633	x 359	x 294	x 242	x 231
n	74	42	34	28	27
e_o	.300	.289	.277	.248	.220

Single pipe

d, in	203				135
t, in	11.2				7.5
V, in^3	10^6 x 129				x 57.5
W, lb	10^6 x 39				x 17
C, $	10^6 x 271				x 121

UP PIPES - Stainless Steel

p_1 = 2900 lb/in^2 (200 bars)
T_1 = 1428 R
T_2 = 992 R
$T_1 - T_2$ = 436 R
T_2/T_1 = .695
$1 - T_2/T_1$ = .305

e_t = .30
e_c = .85
$4f$ = .016
w_o = .08 lb/in^3
s_u = 13100 lb/in^2
w_p = .30 lb/in^3

Multiple pipes d = 18.0 in t = 2.0 in

δ	.0174	.0300	.0500	.1000	.1500
$(\rho_d - \rho_u)gL/p_1$	.0174	.0174	.0174	.0174	.0174
$X - 1$	0	.0126	.0326	.0826	.1326
Y	0	.0036	.0093	.0230	.0363
$\Delta T - \Delta T_c$, R	436	432	425	409	394
ΔT_c, R	0	4	11	27	42
ΔT_t, R	131	131	131	131	131
$\Delta T_t - \Delta T_c$, R	131	127	120	104	89
$\dot{W}$ lb/sec	10^3 x 60.5	x 62.5	x 66.0	x 76.1	x 89.0
P_c/P_o	0	.0315	.0918	.260	.472
J	10^3 x 16.0				
K	116				
$\delta^{1/2}$	.132	.173	.224	.316	.387
V, in^3	10^6 x 850	x 670	x 545	x 448	x 427
W, lb	10^6 x 255	x 201	x 164	x 134	x 128
C, \$	10^6 x 1780	x 1410	x 1145	x 940	x 898
n	208	165	134	110	105
e_o	.300	.294	.282	.254	.226

Single pipe

d, in	153	116
t, in	17.0	12.8
V, in^3	10^6 x 297	x 169
W, lb	10^6 x 89	x 51
C, \$	10^6 x 624	x 355

UP PIPES - Stainless Steel

p_1 = 4350 lb/in^2 (300 bars)

Multiple pipes d = 12.0 in t = 2.0 in

δ	.0262	.0500	.1000	.1500
$(\rho_d - \rho_u)gL/P_1$	.0262	.0262	.0262	.0262
X - 1	0	.0238	.0738	.1236
Y	0	.0068	.0203	.0339
$\Delta T - \Delta T_c$, R	436	428	412	396
ΔT_c, R	0	8	24	40
ΔT_t, R	131	131	131	131
$\Delta T_t - \Delta T_c$, R	131	123	107	191
$\dot{W}$ lb/sec	10^3 x 60.5	x 64.5	x 74.0	x 87.0
P_c/P_o	0	.065	.224	.440
J	10^3 x 36.0			
K	.116			
$\delta^{1/2}$	.162	.224	.316	.387
V, in^3	10^6 x 1560	x 1200	x 980	x 940
W, lb	10^6 x 469	x 360	x 294	x 282
C, $	10^6 x 3280	x 2520	x 2060	x 1970
n	382	295	240	230
e_o	.300	.288	.260	.230

Single pipe

d, in	130			106
t, in	21.7			17.6
V, in^3	10^6 x 485			x 321
W, lb	10^6 x 145			x 97
C, $	10^6 x 1020			x 675

B.10.7 Compressor Cost

Rough estimates of the cost of a 2000 MW turbine-compressor are shown in the following table as a function of cavity pressure. To obtain the cost for a given set of operating conditions multiply the 2000 MW cost by the value for P_c/P_o listed in the "up" pipe calculations.

TURBINE-COMPRESSOR COST

Cavity pressure, bars	100	200	300
lb/in^2	1450	2900	4350
Estimated cost, $/kw	50	70	100
Cost for a 2000 MW unit, $	10^6 x 100	x 140	x 200

B.10.8 Heat Exchanger Cost

Only a rough estimate of the cost of the heat exchangers will be made because the results of Section B.6, All Steam Heat Exchangers, indicate that the heat exchanger cost will be only a small fraction of the pipe cost. Under the assumed operating conditions cavity air enters the exchanger at 968°F and leaves at 532°. The temperature of the saturated liquid on the turbine steam side of the exchanger is 482°F. The log mean temperature difference for these conditions is 191°F. Assuming a value for the overall thermal conductance of 300 Btu/hr-ft^2-F and using a basic heat transfer rate of 2000 MW at 0.30 efficiency the area is

$$\frac{2 \times 10^6 \times 3412}{0.30 \times 191 \times 300} \sim 400 \times 10^3 \text{ ft}^2$$

Assumptions and calculations related to estimating the cost of the heat exchanger are shown in the following table.

Pressure, bars	100	200	300
Pressure, lb/in	1450	2900	4350
Assumed tube wall thickness, in	0.125	0.250	0.375
Tube wt, lb/ft^2	5.4	10.8	16.2
Tube wt, 400 x 10^3 ft^2, lb	10^6 x 2.2	x 4.3	x 6.5
Assume gross wt 2 x tube wt, lb	10^6 x 4.3	x 8.6	x 13.0
Cost, Cr-Mo steel at 2.50 \$/lb, \$	10^6 x 10	x 22	x 33

SYMBOLS

T	temperature
R	gas constant
R	degrees Rankine
C	degrees Celcins
F	degrees Fahrenheit
p	pressure
X	pressure ratio
δ	pressure loss, fraction of cavity pressure
Y	$X^{(\gamma-1)/\gamma}-1$
L	length of pipe, depth of cavity ($L = p_1/w_{ob}$)
w	specific weight
ρ	mass density
γ	ratio of specific heats c_p/c_v
c_p	specific heat, constant pressure
c_v	specific heat, constant volume
e	efficiency
g	gravity constant
P	power
$\dot{W}$	mass flow rate
f	pipe wall friction factor
A	total pipe area for flow
n	number of pipes
d	diameter, inside
D	diameter, outside
t	thickness
s	stress
J	$2p_1^2/(sw_{ob})$
K^2	$\frac{4f}{w_{ob}}\,\frac{RT_1}{2tsg}\,\frac{3}{2\delta}$
V	volume of pipe material

W	weight of pipe material
C	cost of pipe material
\$	dollars

$\Delta T = T_1 - T_2$

$\Delta T_t = (T_1 - T_2)e_t$

$\Delta T_c = T_2 Y/e_c$

SUBSCRIPTS

1	cavity
2	leave heat exchanger
3	leave compressor
u	up
d	down
hx	heat exchanger
t	thermal
c	compressor
o	output
ob	overburden
p	pipe

B.11 PACER - PRELIMINARY ENGINEERING CRITERIA (L. Gore)

B.11.1 *Cavity Operating Conditions*

Sufficient work has not been completed to make possible a "system-analysis" determination of the cavity operating pressure. Presently a range of cavity pressure is being considered, with a tendency toward the lower pressures because of the significant reduction in cost of the primary loop pipes.

Cavity maximum pressure, bars	200	-	320
Cavity minimum pressure, bars	167		267

The increase in pressure during energy addition is usually assumed to be 20 per cent of the minimum pressure.

Operating temperature is fixed by the strength and creep characteristics of salt and is specified as

Temperature, °C	maximum	575
	average	525
	minimum	475

During energy addition, the reflected pressure at the cavity wall has a peak overpressure roughly equal to the steady cavity pressure. The decay is roughly uniform and disappears after roughly 50 to 100 msec. The pipes and injection conduit must be designed to withstand the traveling pressure pulses generated by application of the reflected pressure pulse to the open end of the pipe. In pipes filled with steam or air the overpressure may be attenuated significantly as it travels the length of the pipe, but for the liquid filled pipes the attenuation is likely to be quite small.

B.11.2 Containment

The cavity maximum pressure is limited to 75 per cent of the overburden pressure. This provides a basic tangential compressive stress in the cavity walls which will tend to close cracks and eliminate imperfections. It is recognized that progressive heating of the cavity walls will increase the plasticity of the salt and that the state of stress in the region of the cavity wall will eventually approach a hydrostatic condition. The lower pressure also eliminates the possibility of a major structural blowout under conditions where an extreme fault might develop.

cavity maximum pressure, bars	200	320
overburden pressure , bars	267	400
depth, km	1.21	1.82
depth, ft	4000	6000

Fatigue failure is another problem associated with containment, i.e., after a few years of continuous operation cracks or faults may propagate to the condition where integrity of the cavity might be threatened. Assuming a 20 year operating lifetime and from one to ten cycles per day, the total number of fatigue cycles will be in the range of 7,000 to 70,000.

The other major containment problem is associated with the integrity of drilled holes and mined shafts leading from the surface to the cavity. These passages will contain pipes and the pipes must be sealed to the walls of the hole or shaft to prevent leakage from the cavity. Problems exist where the holes and pipes penetrate the cavity wall as differences in thermal expansion and deformation under load between the salt and the pipes tend to rupture the seal contact and possibly fracture the salt.

There appears to be a problem with pipes which operate at a temperature somewhat less than the cavity steam temperature (475 - 575°C). In the vicinity of the cavity penetration, steam will condense on the colder pipe wall and on the adjacent cold salt. Salt will dissolve in the condensate and will be carried by gravity along the pipe wall and into the cavity. Continued action could lead to destruction of the pipe seal along a significant length of pipe and also produce large voids in the salt and/or regions of fall-out in the wall of the cavity.

Currently, the only solution for this problem appears to be one of permitting only hot pipes (at cavity steam temperature) to contact the salt. This means that pipes would be installed in shafts with the hot pipes surrounding the colder pipes. Examples of the colder pipes are those used for return of the liquid from the surface heat exchangers at a temperature of around 300°C or the pipe used for injection which preferrably should be close to atmospheric temperature.

This method has the advantage of heating the salt adjacent to the hot pipes so that it is in a more plastic state and in a better condition to insure sealing by plastic flow. Some sort of filling material will be required for the voids that will exist between the pipes and the shaft wall. Salt is possibly the ideal material if it can be deposited in the proper form; however, it may be necessary to develop a form of grout or "saltcrete" as has been done for other underground testing projects.

Another advantage of the use of shafts is that emergency blowout preventers and emergency closures can be installed at various locations; for example, at 1000 ft intervals along the shaft.

The oil and gas exploration and production industry has developed various solutions to the high pressure sealing and closure problems. Their talent should be engaged for solutions to these problems and only after some preliminary designs based on existing knowledge have been determined should engineering development tests be started.

It appears that expansion joints will be required in the pipes, located at intervals of something like 1000 ft. This probably means that anchor points located at the expansion joints will be required to support the length of pipe between expansion joints.

The problem of insuring the integrity of the salt and of preventing fall-out in the region of penetration is difficult. However, the use of shafts for multiple pipes makes it possible to enter the cavity and erect protective or equalizing plates at the penetration point. If these can be grouted in place to insure proper load disposition, it appears possible to eliminate failures at the penetration.

B.11.3 Injection

The mechanics of the injection operation occurs at minimum cavity pressure, but the system must be designed to withstand maximum cavity pressure and the shock wave pressure pulses in the conduit produced by the reflected pressure at the cavity wall.

It is expected that the conduit will operate at near atmospheric temperature, or perhaps no hotter than the approximately 300°C temperature of the returning condensate. If necessary, the steam atmosphere can probably be eliminated by filling the pipe with air. A more definite set of conditions can only be specified after a device-injection system study has been performed.

An air-filled lock will be used for insertion. The device will be lowered by a winch and cable system. Various sections of pipe will be isolated by valves. Provision can probably be made for different stages of arming at different depth levels if desired. Considerable applicable technology exists in the oil and gas industry and efforts will be made to obtain their assistance in preliminary design of this apparatus prior to development testing.

B.11.4 Materials

The major requirement for materials is fixed by the pipes which bring 525 ± 50°C steam from the cavity to the surface. They must withstand cavity maximum pressure plus all or part of the transient pressure pulse. The pipes are classified as a major materials problem because their cost, together with the cost of the return liquid pipes, tends to be a significant portion of the capital cost of the plant.

A material having a long term (10 - 20 yr) creep strength at the cavity operating temperature of 10,000 to 15,000 lb/in^2 is almost mandatory. It must be available in the form of plate and pipe and also as large castings for valves and fittings. It must be available in pipe wall thicknesses of at least 2 inches. Pipe diameters in the 12, 18 and 24 inch range will be required.

The material must withstand corrosion from the standpoint of both structural failure and leakage for both vapor and liquid H_2O throughout the full range of pressure and temperature up to cavity conditions. Various concentrations of NaCl in the vapor and liquid are possible, ranging from something like 0.02 per cent in the cavity steam to possibly close to 50 per cent in some of the condensate.

It must be capable of fabrication by conventional fusion welding methods. It should require a minimum of heat-treatment and inspection after fabrication. It should be capable of having defective segments of welds removed and replaced. Welding should not introduce problems of cracking and intergranular corrosion in or adjacent to the welds.

Stainless steels in the 300 and 400 series are examples of the type of material desired and their cost, though high, appears to be acceptable.

Many other material problems will arise, such as those presented by heat exchangers and liquid (return) pumps. However, it appears that there are suitable materials available for these applications and though they may be expensive, they are within the state of the art and do not represent a significant investment as far as total plant cost is concerned.

B.12 CARBON DIOXIDE AS THE HEAT ABSORBING FLUID FOR THE PACER PROJECT - A DETAILED THERMAL CYCLE ANALYSIS (S. Ridgway)

In Appendix A.10, it is estimated that if carbon dioxide were used as the energy absorbing and heat transport material for the PACER project, an overall thermal efficiency of perhaps 30% could be expected.

The carbon dioxide would be removed from the cavity at a high temperature which was limited by the creep rate of the hot salt cavity wall. It would be returned to the cavity at a low temperature determined by the wish to have a high density of returning fluid to save on the cost of the pipes from the surface to the cavity. From these temperatures and the thermodynamic functions of carbon dioxide the thermal efficiency of an ideal power plant was calculated; and this calculated efficiency was somewhat arbitrarily multiplied by 0.75 to obtain an estimate of the practically attainable real efficiency. It is useful to outline in more concreteness such a possible thermal power plant so that there will be a basis for estimating the capital costs and operating parameters of such a plant.

In the proposed system the cavity contains carbon dioxide at a temperature of over 500°C and a pressure somewhat above 200 bars. Three tubes 3000' in length and three feet in diameter carry the hot gas to the surface. Then the gas is expanded through a pressure ratio of 2.0 to get some shaft work from the top of the cycle, to lower temperatures in a useful way, and to lower the pressure for the sake of reducing the costs in the heat exchangers to follow. The open question in this proposed system is whether there will be so much accumulation of radioactive material in the turbine to make its servicing difficult or impossible. The somewhat cooled and expanded gas is further cooled in a sequence of heat exchangers that provides superheated steam for a set of conventional steam turbines.

The design of the steam plant is somewhat complicated by the fact that the carbon dioxide specific heat is quite constant over the operating temperature range, and thus its heat is uniformly yielded over this range. Water accepts heat at a constant temperature in the process of boiling. Thus a large fraction of the heat that would have come from an appreciable cooling of the carbon dioxide stream would be taken up by water boiling at a constant temperature. The average temperature difference between the CO_2 and the boiling water would have to be at least half the amount by which the carbon dioxide cooled. Large temperature differences cause appreciable entropy creation which reduces the thermodynamic efficiency. As a result of these considerations it was found thermodynamically desirable to boil water at three different temperatures to avoid too large temperature differences between the water and the carbon dioxide. After the carbon dioxide has yielded a major fraction of its heat to the stream power plant, it is further cooled, and pumped back into the cavity.

The carbon dioxide circuit is shown in Figure 1. The average condition of the carbon dioxide in the cavity is chosen to be at a pressure of 223.8 bars and a temperature of 528.4°C. When the gas reaches the surface, the temperature has fallen to 520°C and the pressure to 200 bars. The friction pressure drop in the up pipes is 9.8 bars, and the gravity head is 14 bars. The carbon dioxide is then expanded through a pressure ratio of 2 in doing work in a gas turbine whose mechanical efficiency is assumed to be .87. The mechanical work output of this turbine is 87.4 joules/gm CO_2. The turbine output carbon dioxide at a pressure of 100 bars and a temperature of 440°C is cooled to 100°C in providing heat to the steam plant. This plant succeeds in providing 119.5 joules/gm CO_2 mechanical work from the heat given up by the carbon dioxide. The gas is further cooled to 52.7°C in order to minimize the work of pumping the gas back to the cavity. The conditions in the reinjection section of the carbon dioxide circuit are near the critical point of CO_2, where its

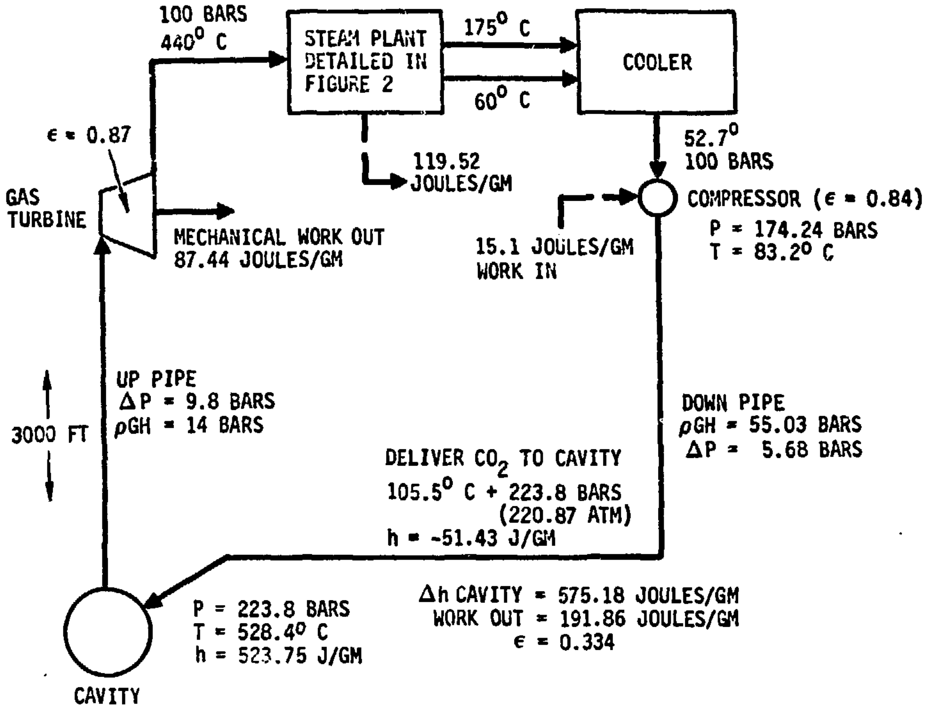


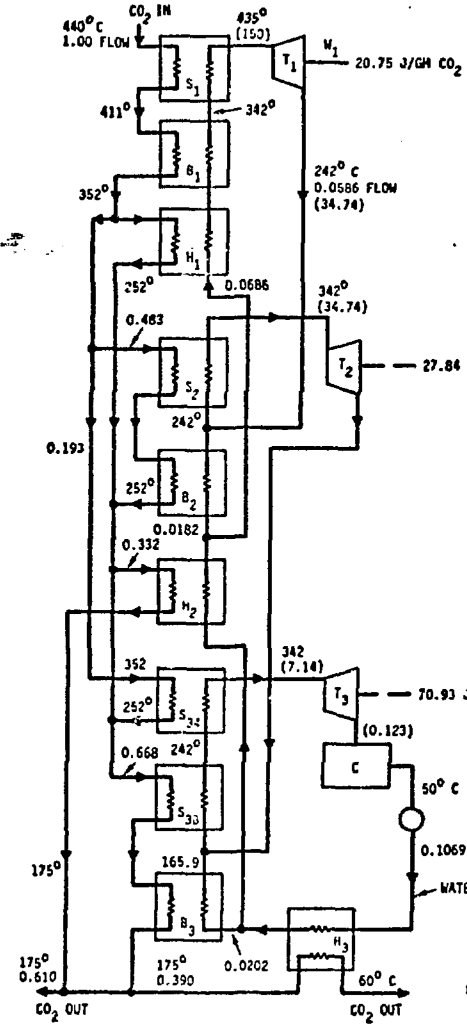
Figure 1. Carbon Dioxide Circuit for Thermonuclear Power Plant

properties are not too far removed from those of a liquid. The specific volume is sufficiently low that the compressor work is fairly reasonable. The compressor or feed pump compresses the 100 bar CO_2 to a pressure of 174.24 bars; the temperature rises to 83.2°C. This gas proceeds down the return pipes to the cavity. There is a friction pressure loss of 5.68 bars in the down pipe. The gravity head is 55.03 bars; and the CO_2 returns to the cavity at 223.8 bars and a temperature of 105.5°C. The 84% efficient compressor used 15.1 joules per gram to compress the CO_2. The net mechanical work delivered by the whole plant is 192 joules/gm CO_2; the enthalpy difference between returned CO_2 and delivered CO_2 is 575 joules/gram. The net overall thermal efficiency is thus 0.333.

B.12.1 The Steam Plant

The steam plant is shown in block diagram in Figure 2. The design procedure was to attempt to make the heat absorption by the water take place moderately uniformly over a range of water temperatures as the carbon dioxide gave up heat over a range of carbon dioxide temperatures. Since the heat of vaporization of water decreases with increasing temperature, the pressure and temperature in boiler B1 were chosen high, i.e., 342°C and 150 bars. The steam is then superheated in countercurrent flow to the CO_2 in superheater S1 almost to the temperature of the incoming carbon dioxide. It is then expanded in turbine T_1 until it becomes wet where it provides 20.75 joules/gm CO_2. The temperature and pressure turn out to be 242°C and 34.75 bars. This temperature is chosen to be that of the second boiler so that the superheater of the steam from the second boiler can also serve as the reheater of the exhaust from the first turbine.

The steam from the second superheater is expanded until wet in turbine T_2 where it provides 27.84 joules/gm CO_2. The wet steam is merged with the output of the low temperature boiler B3 operating at 165.9°C and 7.14 bars, superheated in 2 steps to 342°C, and expanded to .123 bars, 50°C and a quality of 96% in turbine T3. This turbine delivers 70.93 joules/gm CO_2, and its exhaust is sent to the condenser.



NOTE:
PRESSURES (IN BARS) ARE INDICATED BY NUMBERS IN PARENTHESES

Figure 2. Steam Plant

The design is summarized in Table 1, which gives the flows, enthalpy changes and temperatures of the fluids throughout the system. Flows are all normalized to 1 gm of CO_2 throughput.

The temperature differences for the heat exchangers were chosen simply to be neither too large or too small. The plant could certainly be improved by taking a second cut at these design choices, but it turns out that the estimated costs of the present heat exchangers are well within reason. The total heat exchanger cost is estimated in Addendum 1 to be 21.4 million, and the friction loss in pumping the carbon dioxide through these exchangers to be 17 Mw at 80% load, and 32 Mw at full load.

TABLE 1

		HIGH (In CO_2; out H_2O)				LOW (vice versa)	
Unit	Fluid	Flow	T	Specific Enthalpy	T	Specific Enthalpy	Enthalpy Change (flow xΔh)
S_1	CO_2	1.0000	440	427.35 j/g	410.9	393.4 j/g	33.91
	H_2O	.068555	435	3106.1	342.0	2611.8	
B_1	CO_2	1.000	410.9	393.4	352	324.7	68.73
	H_2O	.068555	342.0	2611.8	342.0	1608.8	
H_1	CO_2	.32384	352	324.7	252	208.06	37.77
	H_2O	.068555	342	1610.5	242	1059.5	
S_2	CO_2	.48348	352	324.7	308.67	274.16	24.44
	H_2O	.086742	342	3085.1	242.0	2803.4	
B_2	CO_2	.48348	308.67	274.16	252	208.06	31.94
	H_2O	.018187	242	2803.4	242	1047.4	
H_2	CO_2	.33181	252	208.06	175	118.24	29.80
	H_2O	.086742	242	1047.37	165.9	703.8	
S_3A	CO_2	.192864	352	324.7	252	208.06	22.50
	H_2O	.106919	342	3146.5	242	2936.1	
S_3B	CO_2	.66819	252	208.06	228.42	180.55	18.38
	H_2O	.106919	242	2936.1	165.9	2764.2	

TABLE 1(Cont'd)

Unit	Fluid	Flow	T	Specific Enthalpy	T	Specific Enthalpy	Enthalpy Change (flow xΔh)
B3	CO_2	.66819	228.42	180.55	175	118.24	41.63
	H_2O	.020177	165.9	2764.2	165.9	700.7	
H3	CO_2	.38993	175	118.24	60	-15.90	52.3
	H_2O	.10692	165.9	700.7	50	211.5	

TABLE 2

HEAT TRANSFER REQUIREMENTS

Unit	Temperature Level	Log Mean ΔT	$\Delta T\ CO_2$	Heat Flux Q MW	$Q/\Delta T_{CO_2}$	Cost ($ Million)
S_1	High	24.3°C	12.15	339	27.9 MW/°C	2.56
B_1	High	30.5	27.5	687	25.0	2.29
H_1	High	10	7.5	378	50.4	4.62
S_2	High	29.8	14.9	244	16.4	1.50
B_2	Low	29.8	27.0	319	11.8	.48
H_2	Low	10	7.5	298	39.7	1.62
S_3A	High	10	5	225	45.0	4.12
S_3B	Low	28.6	14.3	184	12.9	.53
B_3	Low	28.6	25.7	416	16.2	.66
H_3	Low	10	7.5	523	69.7	2.86
TOTAL				3613		$21.24 Million

ADDENDUM 1

Design of Superheater S1

To verify that the heat exchangers will not be too expensive, we will do a preliminary approximate design and costing of the Superheater S1.

The design assumptions are:

1. The heat transfer coefficients on the steam and the carbon dioxide side are equal.
2. Since the steam flow is less than 1/10 the CO_2 flow, friction losses in the steam flow will be neglected, and the CO_2 flow put in the tubes.
3. Mechanical energy is worth 0.8 cents/kwh

Analysis:

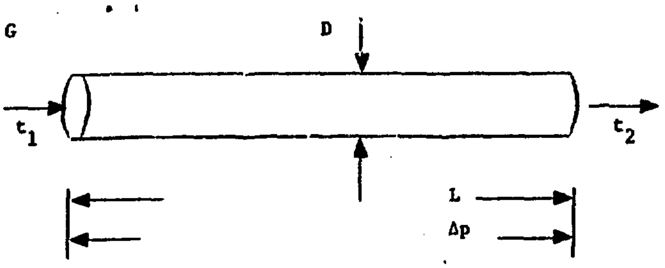
A general heat transfer relation for gases in tubes is

$$\frac{h}{GCp} = \frac{.023}{Pr^{2/3} Re^{.2}} \tag{1}$$

The friction drop in a pipe of length L diameter

D is:

$$\Delta p = \frac{4f\ G^2 L}{2g_c \rho\ D} \tag{2}$$



The mass velocity is G

The weight flow through the tube is $\pi D^2G/4$

This times the temperature rise and the specific heat gives $(t_2 - t_1)\ C_p\pi D^2G/4$ as the heat flow carried out of the heat transfer tube by convection. This must equal the heat flow to the fluid from the wall which is $h\pi DL\Delta T$, where h is the heat transfer coefficient, πDL the surface area for heat transfer, and ΔT the wall to fluid temperature difference. Thus

$$(t_2 - t_1)\ C_p \frac{\pi}{4}\ D^2G = h\pi\ DL\Delta T$$

$$t_2 - t_1 = \frac{h}{GCp}\ \frac{4L}{D}\ \Delta T \qquad (3)$$

The temperature change and the temperature difference have been assigned, h/GC_p (the Stanton number) is a well known heat transfer modulus, and $\frac{L}{D}$ is an important geometrical design parameter.

Combining (1) and (3) and solving for $\frac{L}{D}$ we obtain:

$$\frac{L}{D} = \frac{(t_2 - t_1)}{.023 \times 4}\ \frac{Pr^{2/3}\ Re^{.2}}{\Delta T} = 26.03\ Re^{.2}$$

Inserting $Pr = 1$; $Re \; 3.5 \times 10^5$; $t_2 - t_1 = 29.1$; $\Delta T = 12.15°C$

$$\frac{L}{D} = 333$$

The friction drop is:

$$\Delta p = \frac{4(.003)\; G^2 \;(\frac{L}{D})}{2 \rho \; gc}$$

The friction loss/unit mass is

$$\Delta p \times V = \frac{4(.003)\; G^2\; (\frac{L}{D})\; v^2}{2\; g_c} \qquad v = \frac{1}{\rho} = \text{specific volume}$$

We will now select $D = 1.0$ cm; G remains to be determined. If W is the mass loading the frontal area is W/G. The heat transfer area is 4LW/DG, and it depends on G to the -0.8 power (not the -1 power because of the +.2 power dependence of $\frac{L}{D}$ on the Reynolds number which contains G to the +1 power).

Small tubes are chosen since less wall thickness is needed to withstand the internal pressure; but too small tubes introduce excessive difficulties in fabrication. With 1 cm dia tubes a square cm heat transfer area weighs .62 grams; we double it to allow for shell and support weight, and multiply by \$.0165/gm to get a cost coefficient for a stainless steel heat exchanger of \$.02046/cm^2 or \$204/m^2. From 8766 hours in a 365.25 day year we find that a watt power loss has an annual value lost of \$.07; capitalizing at 14% return on investment and 20 year depreciation, the capital cost of a watt power loss is \$0.46. We now exhibit the total cost as a function of G.

The heat exchange cost is:

$$\$ \ \frac{4W}{G^{.8}} \ \frac{(t_2 - t_1) \ Pr^{2/3}}{.092 \ (\Delta T)} \ \frac{D^{.2}}{\mu^{.2}} \ (.02046) \quad \text{if the}$$

physical variables are taken in CGS.

Inserting numerical values, the heat exchanger cost becomes

$$C_A = \$ \ \frac{107204500}{G^{.8}}$$

The capitalized friction cost is

$$C_F = \frac{(\text{capitalization factor}) \times W \times 4\times(.003) \ G^2 \ (26.03 \ Re^{.2})(13.14)^2(LF)^3}{2}$$

$$= \$.46 \times 10^{-7} \ \text{sec/erg} \times 10^7 \ \text{g/sec} \ (.012) \ G^2(26.03 \ R_e{}^{.2})(13.14 \ \text{cm}^3/\text{g})^2(.8)^3$$

$$= \quad 32.25 \ G^{2.2}$$

$$\text{Total Cost} = \frac{1.072 \times 10^8}{G^{.8}} \quad + \quad 32.25 \ G^{2.2}$$

Set

$$\frac{dC}{dG} = 0 = \quad -.8 \ (1.072) \times 10^8 \ G^{-1.8} + 2.2 \ (32.25) \ G^{1.2}$$

and solve for the optimum value of G

$$G^3 = \frac{.8(1.072)\times 10^8}{2.2(32.25)} = 1208738$$

$$G = 106.523 \quad gm/cm^2/sec$$

Thus we obtain:

Heat exchanger cost = \$2,560,000

Friction loss at 0.8 load = 2.02 MW

Friction loss at full load = 3.95 MW

The total heat exchanger cost is estimated by scaling these results to the other heat exchangers. The low temperature heat exchangers are expected to cost less per unit of heat transfer area since less expensive and more easily fabricated steels may be used. The area cost constant is taken to be 1/3 of that for stainless steel, which upon repeating the minimization yields a low temperature heat exchanger cost .447 that of the high temperature one. Since the low temperature exchanger is cheaper, it pays to save mechanical energy by using more heat exchanger surface and a lower mass velocity. The estimated costs of the individual heat exchangers are presented in Table 2. The total heat exchanger cost comes out to be \$21.2 million. The total friction loss at .8 load is 16.8 Mw, and at full load it is 32 Mw.

APPENDIX C. PROJECT 5--SAFETY, ENVIRONMENTAL AND SECURITY CONSIDERATIONS

C.1 RADIOACTIVE ASPECTS OF ELECTRIC POWER GENERATION BY THERMONUCLEAR EXPLOSIONS CONTAINED IN SALT DOMES (THE NITROGEN AND STEAM SYSTEMS)

(U) (G. Safonov)

This section is issued separately and is classified SECRET-RESTRICTED DATA. The volume is entitled "Appendix C.1 to Project 5--Radioactive Aspects (U), under the main heading "Project PACER Final Report."

C.2 ELASTO-PLASTIC CALCULATIONS (R. Milton)

Calculations were performed using a Lagrangian finite-difference code with one-dimensional spherical geometry. The cavity simulated was 200 m radius located 800 m below the surface. A hysteretic equation of state was used with an initial density of 2.16 g/cm^3 and a compacted density of 2.24 gm/cm^3. The assumption was made that the initial stresses were zero everywhere. Two cases were studied, differing only in the pressure impulses incident on the cavity wall. The two impulse profiles used were:

1. An exponentially-decaying impulse with a peak pressure of 400 bars and a 10 ms e-folding time.
2. An impulse taken from a calculation using Harold. This impulse has a peak pressure of 200 bars and a half-power full-width of approximately 40 ms.

The peak displacements of the cavity wall calculated were approximately 2 in. for case 1 and 3.75 in. for case 2. For both cases the wall returned to nearly its original position within the time range spanned by the calculations. The maximum tensile stresses at the wall were less than 5 bars for both cases. Since the initial lithostatic compressive stresses are several hundred bars at the cavity wall, the cavity wall will never go into tension.

Initial attempts have been made to re-run the simulations with an initial stress distribution corresponding to lithostatic equilibrium. This has proven to be more difficult than originally anticipated and no definitive results have been obtained as yet.

C.3 ON THE INTERACTION OF STEAM WITH THE CAVITY WALL (S. Ridgway)

In the Pacer program it is proposed to generate electrical power from the energy released in thermonuclear explosions by absorbing it in a large mass of steam contained in an underground cavity that has been excavated from a salt dome. The hot steam would be conducted to the surface, where heat would be extracted from it to operate a conventional thermal power plant. The cooled steam would be returned to the cavity for reheat. It is also proposed to choose the conditions of temperature and pressure inside the cavity such that gas and solid are the two stable phases of the system $NaCl-H_2O$.

Sourirajan and Kennedy[1] have extensively studied the system $NaCl-H_2O$ in the pressure and temperature range of interest here. Their Figure 6 is reproduced with addenda on the next page.

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[1] S. Sourirajan and G. C. Kennedy, American Journal of Science 260, 115-141, February 1960.

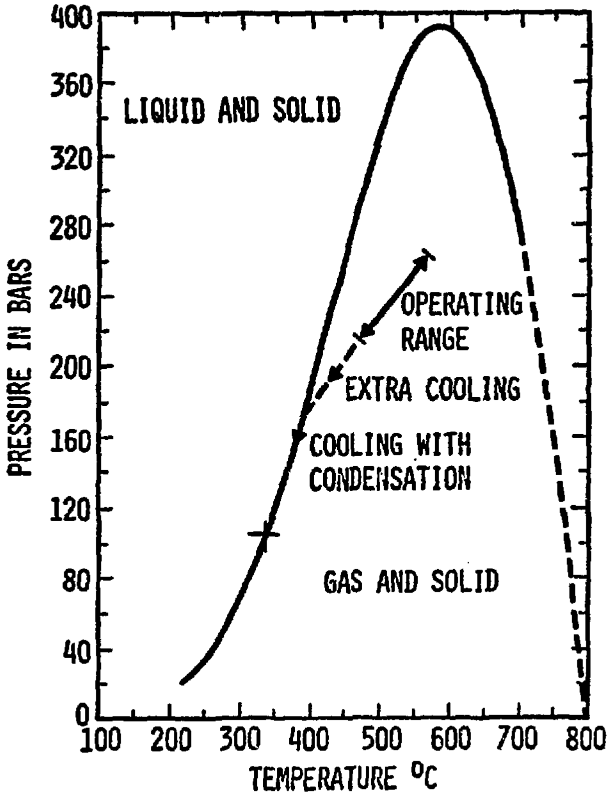

Figure 6. Determinations of the Three-Phase Vapor Pressures in System H_2O-NaCL made on Rising and Falling Temperatures

The curve in Figure 6 is the three phase equilibrium line where gas, liquid and solid stably coexist. Let us confine our attention to the rising part of this curve on the left hand side of the figure. To the left of this rising curve the equilibrium phases are liquid salt solution and solid sodium chloride. To the right of this rising curve the equilibrium phases are gaseous steam and solid salt. The solubility of the salt in the gas phase is very modest, and it is planned to operate on the right hand side of the three phase equilibrium line in order to take advantage of this limited solubility. As long as the conditions of temperature and pressure of the steam can be maintained in this region, one would expect little attack on the wall. A possible operating path for the system has been added to this figure. The average condition is chosen to be 240 bars and 525°C. A plus and minus 10% pressure fluctuation would give a pressure range from 216 bars to 264 bars and a temperature range from 478°C to 573.6°C. The low pressure and temperature end of this operating range is getting near to the point where liquid salt solution form on the wall of the cavity, washing salt down to the bottom. The significance of this is that if there were some failure in the machinery to inject the next explosive device for a day or two, it would not be wise to attempt to limp along cooling the system further to carry the station load until the next explosions were possible. The range could be increased by lowering the mean cavity pressure to the 160 to 200 bars region, but this reduces the operating depth, and probably would require a reduction in the yield per device.

It will be instructive to attempt to estimate the amount of salt that would be brought into solution as a result of overcooling of the steam in the cavity. First, let us assume that the cold steam or water brought back from the surface is well mixed and extensively distributed with the cavity steam, which seems to be necessary in order to avoid cold steam currents that could erode the cavity wall during normal operation. Further assume that the steam cools slowly enough so that mass and heat transfer at the wall is not the rate limit to the process, but rather that the rate at which heat is extracted from the steam by the power plant is the rate limiting step. At the assumed standard condition of P = 240 bars and T = 525°C, the specific volume of the vapor is 12.576 cm^3/gm. At a cavity radius of 193 meters, the cavity volume is 3.0113×10^{13} cm^3, and the steam mass is 2.394×10^{12} gms. As the cavity steam cools at constant volume, the temperature and pressure fall, and if continued, would reach the point 391°C and 174 bars on the three phase equilibrium line.

If the plant thermal efficiency is 0.3, and the load 2 gigawatts, the plant could run 1.07 days until the cavity steam cooled to this point where the liquid phase appears. If by continued cooling the system is allowed to proceed along the three phase equilibrium line to a temperature of 355°C and 120 bars, enough heat would be given up to operate the plant for another 0.99 days. Approximately 6.88×10^{11} gms of steam would be condensed, which is slightly more than a quarter of the total charge, and a layer of salt 67 cm thick would be dissolved from the wall of the cavity.

This heat is estimated in the following way. The steam is conceptually divided into 2 volumes, the first of which expands to fill the cavity as the second provides the steam to condense. The ratio of these volumes is determined from the specific volume (17.65) of the steam at the final point (355°C and 120 bars). The heat of condensation of the steam into the liquid salt solution is taken to be the same as the heat of condensation at the same pressure to liquid water at the saturation temperature, and this is taken at the average value of pressure (147 bars) during the system transit along the equilibrium line. The heat contribution of volume one steam in moving from state one to state two is taken to be $\Delta Q = U + \int_{v_1}^{v_2} Pdv$ which is approximately $-\Delta Q = \Delta U + P_{AV} \cdot \Delta V$ $\Delta U = 2$ joules/gm $P_{AV}\,\Delta V = 74.6$ joules/gm. $\Delta Q = -76$ joules/gm: total $= -1.30 \times 10^{14}$ joules. Note that this steam actually absorbs heat in going from state one to state two.

The mean heat of condensation is taken to be 1020 joules/gm, and subtracting the heat loss in steam one we find the net heat available to be 5.72×10^{14} joules.

More serious to the feasibility of the use of H_2O as the cavity working fluid is the question of whether there will be defects in the wall by which the steam will be able to penetrate to a region of lower temperature salt. Here the steam can condense with the salt to a liquid phase with approximately 50% salt content. This liquid may run back through the hole, crack, or fissure into the cavity, and leave the end of the hole exposed for further attack. As the liquid runs back toward the cavity, it encounters hotter salt, and a hotter environment, and it wishes to boil and precipitate the dissolved salt. It might be hoped that this effect might tend to seal off the penetration but the precipitated salt is most likely to be porous and weak. The pressure pulses of the explosions, and the pressure drops due to the cooling of the cavity may be expected to keep such a passage clear. A feature of this mechanism is that the farther such a defect has penetrated into the cold salt, the greater the chemical force available for extending the defect. Consider the steam in the system to be at the design center pressure of 240 bars. Suppose there is a leak through the cavity wall to a place where the salt temperature is 400°C. Such a temperature exists 1.5 meters back from the surface of the cavity wall after a year's operation. The point 240 bars and 400°C is well across the three phase equilibrium line, and one would expect dissolution of the salt to take place rapidly, limited only by the rate that the heat of condensation of the steam can be conducted away.

If the crack or fissure in the wall of the cavity is large, then one should not expect it to be a place of attack. A large crack or opening will be in sufficient communication with the steam in the cavity that its wall will be at the cavity temperature, and the conditions for the formation of the liquid phase will not occur. If the hole is quite small one again would expect it to not present a serious problem, since the drainage away of the liquid would be well inhibited by any salt deposits forming in the channel. The air content of the cavity steam, provided in order to get opacity to the thermal radiation of the fireball will also aid in inhibiting attack since it will not condense in the channel, but accumulate as the steam condenses. It will inhibit the transfer of steam to the salt surface, and reduce the partial pressure of the steam by dilution, and make the gas the stable phase rather than the liquid.

An intermediate size hole seems to be the ones that might give trouble, such as one an inch in diameter and 5 to 10 feet long. It is long enough, and small enough in diameter to expect the temperature at the bottom of the hole to be strongly influenced by the adjacant salt body and not dominated by the cavity temperature, but it is big enough for any liquid to be able to run out. Let us attempt to estimate a lower limit for the rate of advance of such a tube in the following way. The condensation of steam at the side wall of the tube and the end of the tube will bring the temperature of the salt in contact with it to three phase equilibrium value, which is 440°C. Let us take the temperature of the body of salt to be 400°C. The shallowest possible gradient of temperature at the end of the hole would be that at the surface of a sphere at 440°C with steady state heat flow to an infinite bulk material at 400°C. The heat flux from the hemispherical end of the tube under this condition is

$$\phi = 2\pi kr\,(T_r - T\infty)$$

noting that $k = 0.021$ joules/cm°C and choosing $r = 1$ cm and $(T_r - T\infty) = 40°C$ the heat flux ϕ is 5.25 watts. Using the previous result that about 1000 joules must be disposed of to condense 1 gm of water that is going to dissolve 1 gm of salt, the salt dissolution rate is 5.25 mg/sec corresponding to an advance rate of 7.6×10^{-4} cm/sec or 2.7 cm/hour or 65 cm/day.

In one respect this estimate understates the potential rate at which the hole might advance into the cold salt, and in another respect the potential rate is overestimated. The calculation has ignored the transient heat

Pages 361 through 382 were duplicate information pages and have been removed.

charge that would be placed in the salt from the time of first contact until the establishment of the steady state condition, and thus it underestimates the rate of advance. On the other hand the assumed temperature distribution does not satisfy the steady state heat flow equation on the plane that is the boundary between cylindrical flow and spherical flow. These effects might balance each other, or one or the other might predominate. One could attempt more accurate solutions by computer, or other means. However, one usually would prefer to have the results of experiments to examine. The essential mechanisms seem to not depend upon pressure, and it seems reasonable to do the initial experiments with 1 bar steam in contact with 20° salt.

APPENDIX D. PROJECT 7--GEOLOGY, SITE SELECTION, AND CAVITY CONSTRUCTION

(D. Rawson)

D.1 GULF COAST SALT DOMES MORE SHALLOW THAN 3100 FEET

State & County	Dome	Depth (ft)	Remarks
ALABAMA			
Washington County:	McIntosh	410	1 mile diameter - has a brine field on dome run by Olin-Mathieson Co. Other domes may be discovered.

****

State & County	Dome	Depth (ft)	Remarks
LOUISIANA			
Bienville County:	Arcadia	1400	
	Gibsland	885	
	Kings	172	
	Rayburns	115	
	Vacherie	777	
Franklin County:	Crowville	800	
	Gilbert	1778	
Madison County:	Tallulah	3023	
	Walnut Bayou	2740	
Natchitoches County:	Chestnut	2450	
Webster County:	Bistineau	1500	
	Minden	1912	
Winn County:	Cedar Creek	750	
	Coochie	2500	
	Drakes	350	
	Prices	1300	
	Winnfield	200	Carey Salt Co. (Rock salt mine)
Acadia County:	Jennings	2512	
Ascension County:	Sorrento	1717	Kaiser Aluminum & Chemical Co. (Brine-solution mine)
Assumption County:	Neopoleonville	650	Dow Chemical Co. (Brine-solution mine) Hooker Chemical Co. (Brine-solution mine)
Cameron County:	Black Bayou	1035	
	Calcasien Lake	2345	
	Hackberry, E.	2950	
	Hackberry, W.	1960	Olin-Mathiesen Chemical Co. (Brine-solution mine)

State & County	Dome	Depth (ft)	Remarks
Calcasien County:	Starks	1925	Pittsburgh Plate Glass Co. (Brine-solution mine)
	Sulfur Mines	1460	Pittsburgh Plate Glass Co. (Brine-solution mine)
	Vinton	925	
Evangeline County:	Pine Prairie	346	
Iberia County:	Avery Island	Surface	International Salt Co. (rock salt mine)
	Fausse Pointe	823	
	Iberia	805	Caprock at 1,078
	Jefferson Isl.	31	Caprock at 525 Diamond Crystal Salt Co. mine)
	Rabbit Island	15	
	Vermilion Bay	265	
	Weeks Island	88	Morton Salt Co. (Rock salt mine)
Iberville County:	Bayou Bleu	2802	
	Bayou Choctaw	629	Ethyl Corp. (brine-solution mine) Solvay Chem. Div., (brine-solution mine)
	White Castle	2313	
Lafourche County:	Bay Marchand	2114	
	Bully Camp	1296	
	Chacahoula	1100	
	Clovelly	1168	
Plaquemines County:	Garden Island Bay	2014	
	Lake Hermitage	1400	
	Lake Washington	1500	
	Potash	1300	
	Venice	2100	
St. Martin County:	Anse La Butte	160	Gordy Salt Co. (Evaporated salt)
	Bayou Bouillon	1375	
	Section "28"	1190	
St. Mary County:	Belle Isle	137	Cargill Inc. (Rock Salt mine)
	Cote Blanche Is.	298	Monsanto & Cary Salt Co. mine
Terrebonne County:	Bay St. Elaine	1200	
	Caillou Island	2850	
	Dog Lake	1725	
	Four Island Bay	1305	

State & County	Dome	Depth (ft)	Remarks
Terrebonne County (continued):	Lake Barre	750	
	Lake Pelto	1982	
OFF-SHORE			
	Cameron East Block 104 (115)	338	
	Cameron West Block 386	900	
	Delta West Block 30	2833	
	Eugene Island Block 77	1648	
	110	2606	
	126	275	
	175	201	
	184	1156	
	188	2180	
	Grand Isle Block 16	1985	
	18	2266	
	Marsh Island Block 38	2278	
	Pelto South Block 20	560	
	Ship Shoal Block 32	2538	
	154	2992	
	Vermilion Block 164	573	
	120	3084	

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MISSISSIPPI			
Claiborne County:	Bruinsburg	2016	
Copiah County:	Allen	2774	
	Hazelhurst	1700	
	Sardis Church	1102	
Covington County:	Dont	2300	
	Dry Creek	2300	
	Eminence	2440	Transco Gas Storage
	Kola	3048	
	Richmond	1954	

State & County	Dome	Depth (ft)	Remarks
Forrest County:	McLaurin	1933	
	Petal	1739	
Greene County:	Byrd	2058	
	County Line	2169	
Hinds County:	Carmichael	2966	
	Edwards	3026	
	Oakley	2634	
Jefferson Davis County:	Carson	3086	
	Oakvale	2696	
	Prentiss	2550	
Jefferson County:	Leeds	2065	
	McBride	2205	
Jones County:	Centerville	3000	
	Moselle	2300	
Lamar County:	Tatum	1503	AEC Site
	Midway	2522	
Lawrence County:	Arm	1930	
	Monticello	2757	
Lincoln County	Caseyville	3035	
	Ruth	2700	
Marion County	Lampton	1647	
Perry County:	Richton	533	
Simpson County:	D'Lo	2400	
Smith County:	New Home	2590	
	Raleigh	2140	

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TEXAS			
Anderson County:	Bethel	1600	
	Boggy Creek	1829	
	Keechi	2162	
	Palestine	122	
Brazoria County:	Allen	1380	
	Bryan Mound	1112	Dow Chemical Co (Brine-solution mine)

State & County	Dome	Depth (ft)	Remarks
Brazoria County (continued):	Clemens	1380	
	Damon Mound	529	
	Hoskins Mound	1150	
	Sangent	300	
	Stratton Ridge	1250	Dow Chemical Co. (Brine-solution mine)
	West Columbia	750	
Brooks County:	Gyp Hill	1175	
Chambers County:	Barbers Hill	1000	Diamond Alkali Co. (Brine-solution mine)
	Moss Bluff	1180	
Duval County	Palangana	500	Pittsburgh Plate Glass Co. Chem. Div. (Brine-solution mine)
	Piedras Pintas	1350	
Fort Bend County:	Big Creek	635	
	Blue Ridge	230	United Salt Corp. (Evaporated salt)
	Long Point	930	
	Orchard	375	
	Nash	950	
Freestone County:	Butler	312	
	Oakwood	800	
Galveston County:	High Island	1300	
	Block 144	1741	
	San Luis Pass	358	
	Stewart Beach	2640	
Hardin County	Batson	2050	
	Saratoga	1900	
	Sour Lake	719	
Harris County:	Hockley	1000	United Salt Corp. (Rock salt mine)
	Humble	1200	
	Pierce Junction	950	Texas Brine Corp. (Brine-solution mine)
Jefferson County:	Big Hill	1300	
	Fannett	2200	
	McFadden Beach	2603	
	Spindletop	1200	Texas Brine Corp. (Brine-solution mine)

State & County	Dome	Depth (ft)	Remarks
Liberty County	Davis Hill	1200	
	Hull	595	
	North Dayton	800	
	South Liberty	480	
Matagorda County:	Gulf	1100	
	Hawkinsville	450	
	Markham	1417	
Smith County:	Brooks	220	
	Bullard	527	
	Mount Sylvan	613	
	Steen	300	
	Tyler East	890	
	Whitehouse	2000	
Van Zandt County:	Grand Saline	212	Morton Salt Co. (Rock salt mine)
Washington County:	Brenham	1150	
	Clay Creek	2400	
Wharton County:	Boling	975	
	Hainesville	1155	

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SUMMARY

Off Shore	17 domes	None in use
Alabama	1 dome	1 - being mined*
Louisiana	58 domes	14 - being mined*
Mississippi	34 domes	2 - being used - gas storage - AEC test site
Texas	56 domes	9 - being mined*
	166 total	26 total that may not be compatible
	- 26	
	140 potential sites to be further investigated	

* Mining activities include direct underground mining of rock salt; solution mining of brine for use in the manufacture of such things as soda ash or chlorine-caustic soda; and solution mining for evaporation of crystalline salt.

The date in this tabulation is almost totally from the Handbook of World Salt Resources by Stanley J. Lefond, Plenum Press, New York, 1969. This book is current as of 1966 with a few additions before going to press.

D.2 CAVITY HARD ROCK CONSTRUCTION CONSIDERATIONS

Primary considerations for cavity stability of a large underground cavity in hard rock (intrusive granite, 600 feet in diameter, 4,000 feet deep):

Initial State of Stress

Generally near equilibrium, and the excavation of the cavity induces a change of stress. The rate of stress release and mining procedure are important. Typically the K or horizontal stress/vertical stress vary from 0.6 to 3. It is best to have $K \cong 1$. Commonly the vertical stress is greater than pgh and the prinicpal stresses deviate from vertical and horizontal by several degrees.

Size of Opening

Size does not affect the magnitude or distribution of stress if the material is ideally elastic and the depth is greater than 3x cavity diameter. In real practice instability increases with size.

Shape of Cavity

A sphere or a modified sphere with no abrupt alterations of curvature to cause stress risers is best.

Elastic and Inelastic Properties of the Rock

Poisson's Ratio $\sim$0.2; Young's Modules $\sim 10 \times 10^6$ pse; compressive strength $\sim$30,000 pse for granite. Remember that at the cavity wall it is in an uniaxial state of stress and away from the wall it is in triaxial stress. Compressive strength for rock is greater for triaxial loading. The stress redistribution zone around a cavity is $\sim$1 cavity diameter, and the zone of decompression immediately surrounding the cavity is the most critical region for maintaining cavity stability.

Frequency, Orientation, and Degree of Cementation of Joints, Faults, and Other Geologic Discontinuities

These are the primary features that affect the departure of cavity stability from theoretical considerations. Rock bolts tie structural blocks of rock together and aid in the more uniform re-adjustment of the rock to stresses induced by the cavity excavation or other induced loads.

Changed Stress Due to Seismic Activity and to Explosive Loading

This requires a safety factor for cavity stability with multiple shots and over-extended time.

Changed Stress Due to Changed Hydrologic Conditions

Water-saturated cracks will tend to aid stress relief.

Construction of a 600-foot-diameter cavity at 4,000 feet in granite will require an average diameter closure due to the ideal redistribution of stress of about 17". With geologic discontinuities, this redistribution wants to be variable and tends to loosen blocks and initiate cavity failures.

Assuming a massive granitic mass that approaches ideal elasticity, a compressive strength of greater than 7000 psi and $K \gtrsim 1$ construction of a 600-foot-diameter, near-spherical stable cavity at 4,000-foot depth is feasible. The frequency, orientation, and degree of cementation of joints, faults, and other geologic discontinuities; and the changed stress due to seismic activity and to explosive loading are probably most critical.

The U.S. Army Corps of Engineers Feasibility Studies for Large Underground Cavities indicate a number of likely sites in the U.S. The best candidates are in Yuma and Mohave County in Arizona, and Inyo County in California. Favorable sites exist in the West, Midwest and East. They are notably absent in the Gulf Coast Salt Dome region.

The method of mining is probably with a downward-inclined or vertical shaft to the base of the cavity, progressing around the periphery of the cavity to the top with an inclined drift. Withdrawal of rock would progress from the top down and from the central withdrawl shaft to the cavity boundary. Conventional bench blasting or quarrying would excavate the bulk of material. In this manner, the construction can proceed with gradual alteration of stress conditions. Pre-split blasting will be required to prevent overbreakage at the cavity walls. Rock bolts, wire mesh and gunite (cement 4" thick) would be installed as excavation proceeds for mine safety. If additional lining is required for the project, this should also be accomplished then.

The total cost for the construction of the 600-foot-diameter cavity at 4,000 feet deep, including 4" gunite, 1 rock bolt/25 ft^2, and site exploration directly related to construction is \$27 x 10^6 for 1963-64 costs. A preliminary estimate of cost projected to 1980 which would include additional sealing, cooling and structural steel lining would be on the order of \$30 x 10^6. Excavation costs will largely depend upon improvements in hard rock rapid excavation technology helping to offset increased labor and materials costs.

REFERENCES

Feasibility of Constructing Large Underground Cavities, Sponsored by ARPA, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, TR No. 3-648, 1964.

Vol. 1 Background, Site Selection and Summary.

REFERENCES (Continued)

Vol. II The Stability of Deep Large-Span Underground Openings, TR No. 3-046, Work by the Colorado School of Mines Research Foundation.

Vol. III Report on Cost and Constructibility, Work by Jacobs Associates, 503 Market Street, San Francisco, California, Construction Engineers.

An Evaluation of the Factors Influencing the Stability of a Large Underground Cavity, [illegible] 6654, by D. U. Deere, H. L. Langhaar, A. P. Boresi, University of Illinois, Urbana, Illinois, 1959.

APPENDIX E. PROJECT 8--NUCLEAR TEST FACILITY

E.1 RELATIONSHIP OF THE PACER PROJECT TO A THRESHOLD TEST BAN

(H. Hubbard, E. Martinelli)

The goal of the PACER project is to contain the energy released by thermonuclear explosives in a salt dome cavity and to use steam heated by these explosions to operate a conventional power plant. In the course of this project, it is proposed to conduct a series of scaled-down tests using 1 KT nuclear explosions. The cavity for these tests will be constructed at 1 to 1.5 km depth and will be about 80 to 100 meters in diameter. We want to suggest the continued use of this cavity for testing of nuclear weapons after the PACER experiments have been completed. Such a cavity could play an important role in the event of a threshold test ban, and it offers additional advantages as a test facility over underground testing in Nevada.

If a ban on nuclear testing is agreed upon, based on a seismic threshold, then it will be essential for the U.S. to have an adequately decoupled test facility which will allow the continuation of the most important tests. The bulk of U.S. underground testing is done at low yields--3/4 are below 10 KT--and these are also the most important tests for weapon development. It is pertinent, therefore, to examine the effectiveness of the 100-meter diameter PACER cavity as a decoupling chamber for a 10 KT explosion.

Fortunately, there is direct experimental evidence which bears on the question of decoupling. In Project Sterling [1] a 380-ton nuclear device was detonated in a 34-meter diameter spherical cavity in a salt dome near Hattiesburg, Mississippi. The depth was 828 meters and the cavity contained only air at ambient conditions. The high pressure shock on the wall caused by the explosion was attenuated very rapidly in the salt and did not lead to an observable seismic signal. The decoupling factor for the teleseismic signal was approximately 100. Since the strength of the shock at the wall scales as yield/volume for the same ambient pressure, the yield in the 100-meter cavity that would lead to the same shock on the wall is $0.38 \times (100/34)^3 \sim 10$ KT. The 100-meter size can therefore be expected to produce a teleseismic signal appropriate to a 100-ton explosion from an actual 10 KT test.

It is worth noting that, on re-entry, the cavity used for the Sterling experiment was intact, and could presumably have been used for another shot. Similarly, we have no reason to believe that a larger cavity would not be suitable for many explosions. Although the cavity radius is smaller than the fireball radius, and some salt will be melted after each explosion, rough estimates indicate that this is not a serious problem and that the cavity can be used repeatedly. The reusability of the facility will result in a considerable cost savings over that for the underground tests conducted in Nevada. In addition, the containment of the radioactive materials will be much surer than in the Nevada tests.

It is interesting to conjecture that the Russians may already have such a test facility. The AEC has announced two tests greater than 100 KT in the region of the Soviet Union where there are many salt domes. These explosions would have created cavities in the salt domes suitable for conducting decoupled tests in the 10 KT range, just as the U.S. 5 KT Salmon experiment created a stable cavity for the Sterling test.

REFERENCES

1. Sisemore, Clyde J., Leo A. Rogers, and William R. Perret, "Project Sterling: Subsurface Phenomenology Measurements Near a Decoupled Nuclear Event," J. Geophys. Res., Vol. 74, No. 27, December 15, 1969.

APPENDIX F. PROJECT 9--SYSTEM ANALYSIS, COORDINATION AND PLANNING

F.1 PACER--EXPERIMENTAL DEVELOPMENT PROGRAM TO DETERMINE FEASIBILITY (D. Rawson, L. Gore)

F.1.1 Recommendations

An experimental development program designed to establish the feasibility of the PACER concept through a nuclear fueled power producing prototype phase should be started as soon as possible. Total time required through completion of prototype testing is about five years. Total cost for the experimental program is about 25 million dollars*, not including costs for the nuclear devices. The three main parts of the program are:

- o Laboratory testing--5 year period, $7.5 million;
- o 10 Meter diameter cavity testing--2.5 year period, $2.5 million;
- o 100 Meter diameter cavity prototype testing--5 year period, $15 million, not including costs for the nuclear devices.

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*Cost estimates are based on 1973-74 dollars. Assuming costs inflate at 7.5 percent per year compounded annually, the 1978-79 costs will be 40 to 45 percent higher and average costs for the five year program will be 30 to 40 percent higher.

F.1.2 Background

F.1.2.1 Objective

PACER has its greatest value and thus the highest likelihood of financial support if it can be shown that the concept is feasible and this feasibility demonstrated within a relatively short period of time. Associated with this is the need for definitive milestones during the early investigation periods to enable decisions to be made as to the advisability of further development and increased funding. We have thus set an overall goal of full scale PACER energy production and at least a proven prototype nuclear fuel breeding capability within a period of 10 years. This goal implies that the concept feasibility must be proven within 5 years and that initial milestones leading to proving feasibility should be completed within 2 to 3 years.

The above goals appear achievable in large part because of the excellent relevant studies that have been accomplished in support of project Payette, Salmon, and Sterling. This background of detailed analysis, design, field testing, site investigations, and development of experienced personnel helps point to a high probability of success potential for the PACER concept; achievable for a relatively modest additional investment.

F.1.2.2 Questions Regarding Feasibility

1. Are there a significant number of sites likely to be suitable for the application of the PACER concept?

Preliminary review of literature indicates that there are probably 40 to 100 suitable sites in piercement salt structures in the Gulf Coast states of Alabama, Mississippi, Louisiana and Texas. In addition, several sites may prove out in Arizona, Utah and Colorado. Because of the economic leverage associated with breeding in addition to power production, it is

also feasible to consider additional sites and much greater geographical coverage in massive hard rock such as granite.
(Needs additional field data.)

2. Can large cavities be solution mined in salt to the desired shape for "decoupling" and to minimize "stress risers" and thus maximize cavity stability?

The Payette studies indicate that near spherical cavities in the order of 100 meters diameter are a reasonable extension from existing solution mining practice and that the moving air blanket with reverse circulation method holds the most promise for shape control.
(Needs additional field data.)

3. What is the expected cavity stability of a Payette cavity in Dome Salt?

The Salmon cavity was generated using a 5.3 kT nuclear explosive to produce a cavity 38 meters in diameter. The stresses and the heating of the wall rock were much greater than would be produced by PACER. The cavity also was utilized to test decoupling theory with a 0.35 kT nuclear explosive. The maximum cavity size and usable lifetime require further study.
(Requires field testing.)

4. How does the presence of steam effect the strength properties of Dome Salt?

It appears that as long as the cavity contains only dry single phase steam, it will not significantly affect cavity stability. Strength in the presence of steam has not been measured and this is a priority laboratory experiment.
(Requires field testing.)

5. What engineering difficulties are expected in providing repeated access to the cavity for explosive device emplacement?

The petroleum industry technology for containing high pressure natural gas, geothermal wells and oil is extensive and improving under the pressure of increased environmental constraints. Special "blowout preventors and stripping capability" were developed by industry and used for Salmon post shot reentry. Thus it is expected that existing technology can be significantly utilized.
(Requires additional development and field testing.)

6. What happens when steam condensation takes place and salt dissolves?

Condensation of liquid H_2O and consequent dissolving of the salt walls is not expected to occur under normal operating conditions. During an abnormal cool-down it is expected that the hotter walls of the cavity will prevent condensation on the walls.

If cracks in the salt or openings along the pipe penetrations exist and lead roughly radially outward to zones where the temperature is lower than the the temperature required for condensation of liquid H_2O, it may be possible for the defect to propagate by refluxing. Laboratory tests together with development of the theory will give an early answer to the possibility of such problems and their solution. Field testing in the 10 meter diameter cavity will be used to prove practical solutions.

7. What about material corrosion problems--salt, steam, elevated temperature and stress transients?

(Laboratory and field tests are required)

F.12.3 Field Experiment Program Concept

The above examination of key questions regarding the feasibility of PACER is far from exhaustive and the tentative answers are subjective. The purpose is to illustrate the importance of initiating critical laboratory tests, computations, literature reviews and preliminary site selection activities. Many of these activities are underway and it is becoming increasingly obvious that these efforts could and should lead to field tests; thus, getting the program into the real world to test developing knowledge.

There are distinct advantages in conducting the exploratory field tests in a facility which approximates full scale site conditions as closely as possible while still allowing direct personal access to a test cavity for installation of measuring equipment and observation of test results. Also, direct access enables some important experiments which cannot reasonably be accomplished remotely by working through drill holes.

According to Heard's work on the steady-state flow in polycrystalline halite, deformation is relatively independent of confining pressure as long as salt temperatures are in the 200°C to 600°C region. Thus, it is quite reasonable to conduct field test experiments in Dome Salt at a depth of 700-1000 ft (existing salt mine depths). For such a shallow depth experiment, it is required that the cavity walls be preheated to develop a scaled down plastic salt liner surrounding the solution mined cavity.

F.1.3 Experimental Program Definition

F.1.3.1 Introduction

PACER is a method for Electric Power Generation by Contained Thermonuclear Explosions. It offers the only possibility for fission-fusion power generation within the next 10 years.

The time scale for establishment of the feasibility of the method is controlled by the development of the technology of the containing cavity. Cavity technology can generally be divided into two categories, i.e., cavity production or formation and integrity of the cavity under actual operating conditions.

The object of this report is to describe as a function of time and cost a development plan for laboratory, field tests and prototype tests that can be completed in five years from time zero and will establish the feasibility of the PACER concept through the prototype phase.

F.1.3.2 Laboratory Tests

Laboratory tests will extend over the five year period. They will be limited primarily to fundamental problems of structural materials, corrosion, properties of salt and small cavities (3" and 12" diameter) in salt. Internal aspects of the primary loop will be included; but, external problems such as sealing and penetration will be considered to be primarily a design and field test problem. The cost of the laboratory program is expected to vary from about $1 M/year at the beginning to about $2M/year at the end of the five year period for a total of about $7.5 Million.

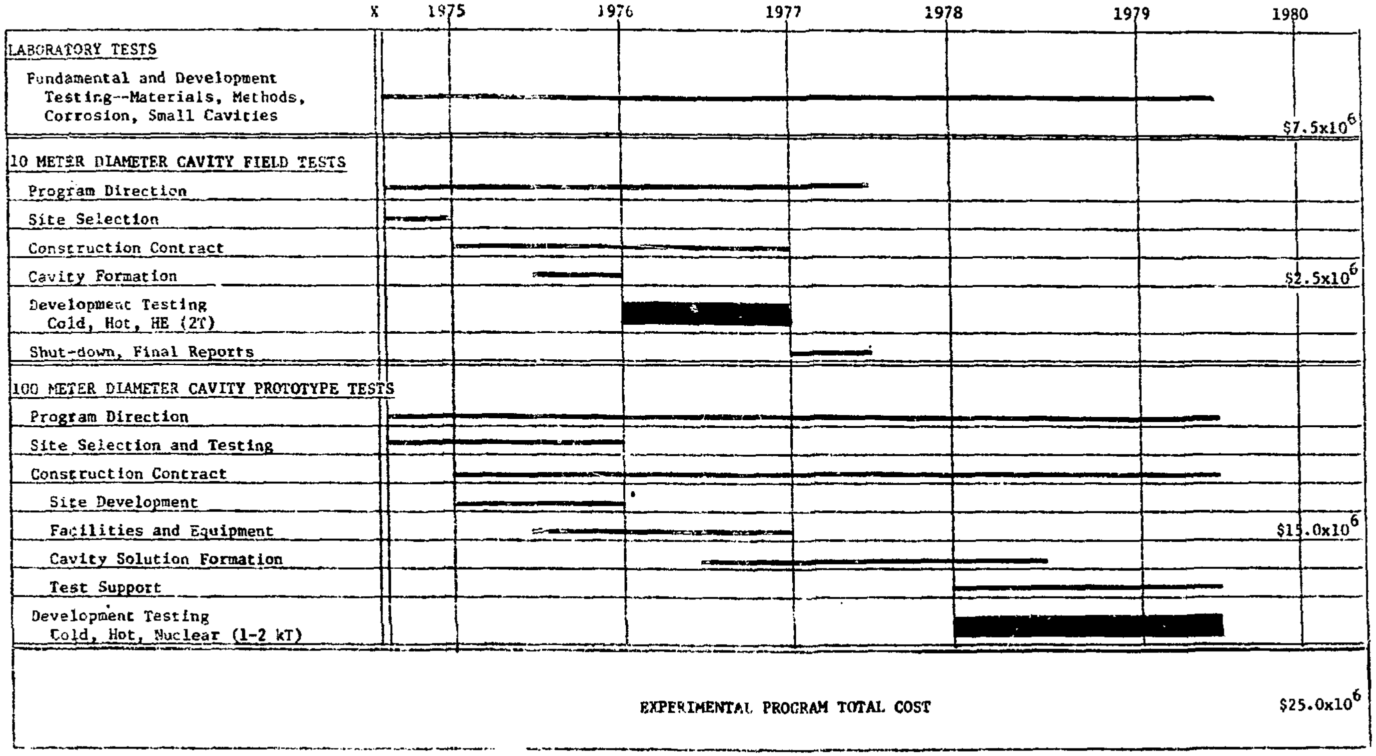
F.1.3.3 10 Meter Diameter Cavity Field Tests

The field tests are planned around the concept of a 10 meter diameter cavity at a depth of 700 to 1000 ft formed adjacent to an existing mine shaft. Manned access through a horizontal tunnel will be provided for instrumentation installation, measurements and inspection. Site selection and engagement of an architect-engineer (AE) would begin at time zero and the cavity would be completed by the end of 1976. Testint with cold air, hot air, steam and HE (~2 tons) pulses would continue for another year. Testing, including verification of seal and penetration designs would be completed by the middle of 1977 at a cost of about $2.5 million.

F.1.3.4 100 Meter Diameter Cavity Prototype Tests

Work on the prototype test would also start at time zero. Site selection, planning and AE construction of topside facilities would continue until about mid 1976 when solution mining of the 100 meter diameter cavity would be started. Two years are allocated for completion of the cavity bringing the time to mid 1978. One and one-half years have been allocated for testing, primarily with hot, full pressure steam and using at least a few nuclear devices estimated to be $15.0 million (not including the cost for the nuclear devices) with completion in mid 1979. Continuous electrical power can be produced in the range of 10 to 50 MW, depending upon the frequency of device injection. All aspects of the full scale PACER system can be investigated and sufficient information can be obtained to determine the feasibility of a full scale (~2000 MW) system.

F.3.5 Experimental Program Time Schedule



F.1.3.5 Cost--10 Meter Cavity Field Test (2.5 yr. completion in late 1976)

	Cost (Thousands of Dollars)
Program direction	
*1S 2J 3 yr	360
Site selection	
1 C 5 yr	40
testing	100
Site lease	
1000 ft shaft	500
AE Contract	
site, test, cavity, support	750
Instrumentation	100
Pipe, seals	50
Compressors, boilers, heaters	100
Tests	
cold air	
hot air	
hot steam	
HE	540
fatigue cycling	
shut-down	
2S 1.5 yr	
3J 1.5 yr	
4T 1.5 yr	
final reports	
TOTAL	2,540

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*Personnel costs including overhead: S - Scientific, $60K/yr; J - Junior scientific, $40K/yr; C - Consultant, $80K/yr; T - Technician, $30K/yr.

F.1.3.6 Cost--100 Meter Cavity Prototype Test (5 yr. completion by mid 1979)

	Cost (Thousands of Dollars)
Program direction	
*1.5S 4J 5 yr	1,250
Site selection	
1C 2 yr	160
testing	500
Site development	1,000
AE contract	
construction	
drilling, shafts	
solution cavity forming	
test support	
material, equipment	8,000
water storage, salt disposal	
Instrumentation	250
Pipe, seals	250
Compressors, boilers, heaters	1,000
Heat exchanger, pumps	1,000
Tests	
cold air, hot air	
hot steam	
nuclear**	
fatigue cycling	
shut-down	
3S 2 yr	1,360
5J 2 yr	
10T 2 yr	
final reports	
TOTAL	14,770

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*Personnel costs including overhead: S - Scientific, $60K/yr; J - Junior Scientific, $40K/yr; C - Consultant, $80K/yr; T - Technician, $30K/yr.

**Costs for nuclear devices not included.

F.2 SYSTEM PARAMETERS FOR MINIMUM COST OF POWER (H. Hubbard)

The major PACER system elements are now well enough understood so that the approximate variation in the cost of these elements with the important system parameters is becoming apparent. In principle, given these formulas it is only a mathematical problem to determine values of pressure, cavity volume, and yield that minimize the cost of power. The choices we have made for these parameters have been dictated by technical considerations in addition to cost, so it is of some interest to know how far they are from the minimum cost values, and whether changes might be dictated.

About half of the total PACER facility cost is independent of the choice of pressure, volume, etc. (see Project 3, p. 13), so at the outset we are working on only about \$200/kW(e) out of ~\$450/kW(e) (projected 1980 dollars). The cost of the fuel is additional.

F.2.1 Major Cost Elements

The units and symbols are as follows:

Item	Unit	Symbol
Costs	$\$10^6$	
Volume	10^6 m^3	V
Cavity pressure	200 bars	p
Peak electric power	GW(e)	P
Energy per charge	Mt	E
Cost of electric energy	Mills/kWh(e)	e
Annual charge rate	fraction	i

Cost of cavity and shaft:

$$C = a + bV^{\beta}, \quad \beta = 0.4418 \qquad (1)$$
$$a = 5, \quad b = 30$$

The value of the exponent comes from the Payette study. There is also a slight pressure dependence, probably of the form of a factor

$$1 + \gamma(p-1)$$

with γ probably $\sim.25$. This will play almost no role in the results and will be ignored.

Cost of pipes:*

$$D = dp^{\alpha}, \quad \alpha = 3.5 \qquad (2)$$
$$d = 150$$

Cost of fuel charge:

F probably has a value between .01 ($10K) and .2 ($200K). This is treated as a parameter.

Cost of containment system:*

This is least well known, but is roughly

$$G = gpV, \quad g = 5 \qquad (3)$$

F.2.2 Constraints

The only constraint assumed is the value of the insult parameter, which is chosen to assure no tensile stresses. Although it may be possible

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*Private communication with L. A. Gore.

to change its value safely, the insult parameter in current use is not allowed to vary, i.e., the value of

$$k = \frac{pV}{E} = 283 \frac{m^3}{ton} \tag{4}$$

is treated as a constant.

F.2.3 Operating Assumptions

The number of hours per year of plant operation is assumed to be

$$H = 7000 \text{ hours.}$$

The thermal efficiency for conversion of thermal to electrical energy is taken to be

$$\eta = 0.30$$

The power level P is left unspecified and is treated as a parameter. The number of explosions per year, n, is given by

$$1160\eta En = HP,$$

(There are 1160 kWh per ton of yield.)

Using the above numbers this becomes

$$nE = 20.1P \tag{5}$$

F.2.4 Cost Minimum

The cost of power in mills/kWh is given by

$$e = \frac{10^3 i}{HP} \left(\text{fixed costs} + C + D + \frac{nF}{i} + G \right) \qquad (6)$$

We add to this the function $\lambda\left(k - \frac{pV}{E}\right)$, where λ is a LaGrange multiplier, in order to take Eq. (4) into account and simultaneously treat p, V, and E as independent variables. We then have four equations, the three variations plus Eq. (4) to determine p, V, E and λ. Equation 5 is used for n.

$$\frac{nF}{i} = \frac{(20.1)PF}{0.15\ E} = \frac{f}{E} \qquad (7)$$

where $f \equiv 134\ PF$

The variation yields the equations

$$\delta E: \quad -f + \lambda pV = 0 \qquad (8)$$

$$\delta p: \quad \alpha d p^{\alpha-1} + gV - \frac{\lambda V}{E} = 0 \qquad (9)$$

$$\delta V: \quad \beta b V^{\beta-1} + gp - \frac{\lambda p}{E} = 0 \qquad (10)$$

These three equations plus Eq. (4) define the minimum.

Equations (9) and (10) yield

$$\alpha d p^{\alpha} = \beta b V^{\beta}, \qquad (12)$$

which relates pressure and volume at minimum cost independent of either fuel costs or containment vessel costs. This is a consequence of the pV dependence of both the containment cost and the constraint. Equation (12) holds provided both p and V are allowed to vary, i.e. provided Eqs. (9) and (10) both hold.

Using Equations (12) and (4) in Eq. (9) one obtains

$$\alpha d p^{\alpha+1} V + g(pV)^2 = kf \qquad (13)$$

where, (Eq. 12) $V = \left(\frac{\alpha d}{\beta b}\right)^{1/\beta} p^{\alpha/\beta}$

To obtain numerical values we now drop the containment term, assuming it is fixed, in order to make the work simple, by putting $g = 0$.

Then a solution is:

$$p^{\alpha+1+\alpha/\beta} = \frac{kf}{\alpha d}\left(\frac{\alpha d}{\beta b}\right)^{-1/\beta}$$

along with Eq. (12) for V and

$$E = \frac{pV}{k} .$$

Inserting numerical values

$$\begin{aligned} p &= 0.732(FP)^{0.0805} \\ V &= 291(FP)^{0.6377} \qquad (14) \\ E &= \frac{pV}{283} \end{aligned}$$

The following table results

FP	p (bars)	V $10^6 m^3$	Diameter (m)	E kT	Fuel Charge Cost for P = 2GW ($\$10^3$)
.01	101	15.46	309	28	5
.05	115	43.1	435	87	25
.1	123	67.1	504	146	50
.2	129	104	583	237	100
.4	136	162	676	389	200

These values are characterized by low pressure and large volume--too large to be practical.

If the cavity volume is chosen in advance and not allowed to vary, the results are different. Equations (10) and (12) are no longer present, and one obtains from Equations (4), (8) and (9)

$$p = \left(\frac{kf}{\alpha dV}\right)^{1/1+\alpha} = 2.588 \left(\frac{FP}{V}\right)^{0.222} \quad \ldots \qquad (15)$$

Fixing the cavity diameter at 300m, V = 14.14, and using FP = 0.2, Eq. (15) gives

$$p = 1.005 \text{ (200 bars)}$$

and

$$E = \frac{14.14}{283} = .05 \text{ (50 kT)}.$$

These are the present PACER choices, and correspond to the rather conservative assumption of a $100K cost for a 50 kT charge--$2 per ton of yield.

F.2.5 Effect of Breeding

As long as the same components are used for the system, breeding does not change the minimum cost choices, assuming a fixed return, for example, \$10/gm for ^{233}U or Pu. If one mole of neutrons/kT are caught in fertile material (thorium):

$$\text{no. of gms/year} = 233 \times 10^3 \text{ En},$$

and

$$\text{credit for breeding} = 2.33 \text{ En \$M/year}$$

Reduction in cost of electricity is

$$\frac{10^3 \times 2.33 \text{ En}}{\text{HP}} = \frac{10^3 \times 2.33 \times 20.1 \text{ P}}{7000 \text{ P}} = 6.69 \frac{\text{Mills}}{\text{kWh}}$$

Consistent with present assumptions, this savings is a fixed number, independent of system parameters. The re-design of the system to emphasize breeding has not yet been undertaken.

Ref. 4

RDA-JTR-4100-002
(REVISED)

FUSION POWER IN TEN YEARS -- PROJECT PACER

JULY 1974

Sponsored By:
U.S. ATOMIC ENERGY COMMISSION
Washington, D.C. 20545

Contract No. AT(29-2)-3324

R & D ASSOCIATES
Post Office Box 3580
Santa Monica,
California, 90403

los alamos
scientific laboratory
of the University of California

PREFACE

PACER is a concept which utilizes known technology to achieve electric power from fusion explosions. The purpose of this paper is to present our current views of the implications of PACER development and to indicate the program and funding required to accomplish complete development as rapidly as is consistent with good practice.

The importance of the PACER concept was recognized by scientists at R & D Associates (RDA) who also became convinced of its practicality through their familiarity with feasibility studies of the construction of large cavities for seismic decoupling of nuclear tests [1, 2]. In October 1972, RDA proposed a development of the PACER concept [3] and were quickly joined by the Los Alamos Scientific Laboratory (LASL) in this effort. In July 1973, the AEC funded a joint effort study program with LASL and RDA. This study is directed mainly at questions of safety and feasibility of containing the repeated explosions in underground cavities, but some other questions have also been addressed. Highlights of the first year's work are summarized in Appendix 1. So far, no natural, logical, or economic barriers have been found which would preclude development of the concept.

The ideas and work described here have been contributed by many individuals. The report was written by H. W. Hubbard, Program Manager of the PACER Project at RDA.

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THE CONCEPT

The idea is to use clean, thermonuclear explosives to heat steam contained in a large underground cavity and to use the steam to operate a modern conventional electric power plant. The primary motivation for this concept is that it makes available the enormous reserves of low-cost energy which can be released by the nuclear fusion of heavy hydrogen (deuterium). Perhaps equally important for the short term is that burning deuterium is accompanied by the release of neutrons which can be used to provide a plentiful source of reactor fuel--about 20 gm of enriched fuel for each gram of deuterium consumed. Unlike the other programs which propose to obtain energy from fusion (magnetic confinement and laser fusion), the technology for accomplishing the nuclear fusion by explosive means is proven and successful as a result of the AEC weapon development program. The PACER concept is a valuable civilian spinoff from the large sums of money spent for defense. Almost all the basic technology of the power production scheme is available, requiring only engineering development supplemented by a very modest scientific research program.

We believe that the twin benefits of this development--commercial fusion power plants and a plentiful source of reactor fuel--can be achieved in about ten years, much more rapidly than the present fusion program can hope to accomplish them.

POWER PLANT

Typically, the underground cavity required for a PACER steam tank would be from 100 meters to 400 meters in diameter, depending on the energy of the fuel charge. This will be no more than 100 kT of fusion with very little associated induced activities or fission products.

The rate of firing the fuel charges determines the power station capacity; for example, a 2000 megawatt electric power plant requires a 50 kT charge

800 times per year, or about twice a day. (A 30% net efficiency and an 80% load factor have been used to obtain these numbers.) A steam loop, heat exchanger, containment system, and conventional turbine generator make up the remainder of the plant. A sketch of this system, which is our baseline unit, is shown in Figure 1.

A backup alternative power plant based on CO_2 rather than steam as a working fluid has been worked out conceptually in case unforeseen chemical-geological problems arise at the steam salt interface. The CO_2 seems satisfactory as a working fluid, with essentially the same resulting thermal efficiency.

Security for the plant must be provided to prevent theft of enriched fissile material, but no assembled explosives will be available. Assembly will be accomplished during insertion of explosive parts into the cavity, thus a premium is put on simple explosive design.

It is envisioned that PACER facilities will most likely take the form of completely enclosed power complexes. Materials recovery and reprocessing plants and fuel fabrication would take place within the complex so that no highly enriched fissile material would ever be shipped. (See section on thorium utilization.)

SAFETY

The safety and environmental aspects of a PACER power station present no difficult conceptual problems, and there are some distinct advantages over conventional nuclear plants.

Within the cavity, the small amount of generated radioactivity--a few percent of that from an equivalent reactor--is diluted by the very large ($\sim$1 million ton) steam inventory, to the order of a few parts in a hundred million after one year. As the steam is circulated, however, a filtering system will remove the particulates, precipitate soluble

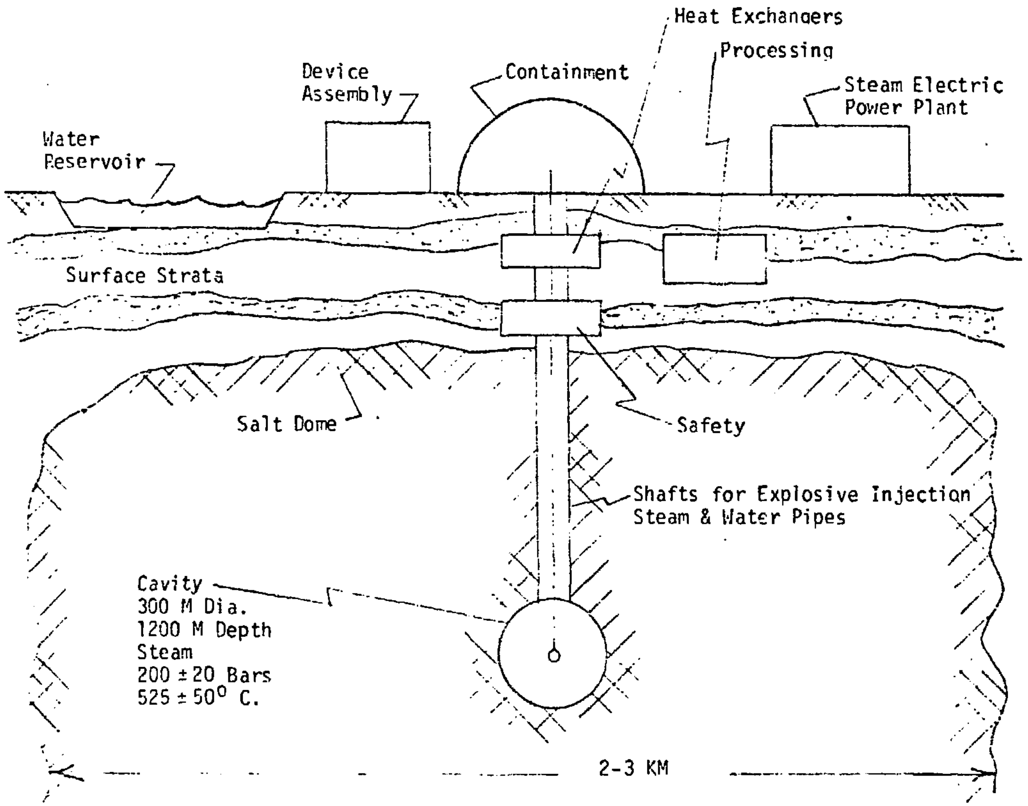

Figure 1. Concept -- 2000 Mw Powerplant

products and will purge gases. Since the steam circulates about once every three days, the concentration of fission products will be kept very low--about one curie or less per ton of steam. If this were dispersed at atmospheric pressure above ground, the concentration would be $\sim 10^{-3}$ μCi/ml. The total inventory of fission products in PACER at any time is no more than a tenth of a percent of that accumulated in an equivalent fission power reactor on the average.

The only unusual radioactive nuclide present in a PACER reactor in quantity is tritium (^3H) produced by the explosions. ^3H emits a very low energy electron with a 12-year half life. It is not a particularly hazardous material compared to the α and γ-emitters and will be bound in the water as HTO so that it cannot be released as a gas. The tritium produced annually will be ∿40 Kg or four parts in 10^8 of steam.

Above ground, an emergency containment and suppression system will be provided. These will include a pressure vessel and a small lake with enough water to combine with and condense any escaping steam which would then be trapped in a covered catch basin or in the cavity itself.

Seismic effects, which are peculiar to PACER are kept small: the baseline 2000 Mwe station produces "thumps" so small as to go unnoticed a few miles from the site.

The question of the possibility of a gross cavity failure is not only a question of safety but one of feasibility. It is the key question of this project. The main thrust of all the research and development work is to determine whether the cavity stands up under prolonged use. Every effort is being made to conceive possible failure mechanisms. Most importantly, repeated testing in the laboratory, in the field, and in the prototype will be used to test the cavity integrity under all conditions of interest. Discovery of a basic flaw in the concept would, of course, terminate the work. No such flaw has been found to date.

Finally, it should be pointed out that there is no chance that an excessively large energy release could occur from one of the fuel charges. These can be designed so that the maximum practical energy release of which they are capable is also the desired amount. Any failure then leads to a reduced energy release, which is never dangerous. A zero energy release, or dud, can be provided for by designing the charge to be rendered inactive by the cavity environment within a short time.

POTENTIAL AS AN ENERGY SOURCE

The location of PACER power plants in salt domes is a natural choice because the domes are quite pure, are large enough to accommodate the PACER caverns which can be constructed cheaply by solution mining, and most important, because salt is a plastic, self-sealing material at the PACER operating conditions. These salt domes are located mainly in the gulf coast area of the U.S. Although more electric power is needed in that region [4], distribution of PACER electricity to other areas of the U.S. would be a problem. For this reason, lined caverns in rock are also under consideration, since hard rock is not limited to a single geographical area. While studies have been made of the feasibility, cost, and methods of cavity construction [5, 6], the technology of providing suitable linings for these rock caverns needs development.

Preliminary surveys of salt domes indicate a potential possible deployment of PACER yielding electric power plant capacity comparable to the present U.S. electrical generating capacity (∿400,000 Mwe). If lined rock cavities prove to be feasible, the potential peak generating capability would be substantially larger.

POTENTIAL AS A FUEL BREEDER

An additional, very important benefit of fusion power from deuterium burning is the possibility of producing ^{233}U or ^{239}Pu by utilizing the excess neutrons available from this process. In this aspect, PACER is much superior to the two major fusion efforts sponsored by the AEC (CTR and Laser-Fusion), because they are planning to burn a deuterium-tritium (D-T) mixture in their first applications, not pure deuterium (D-D). (Burning of pure deuterium is roughly another order of magnitude of difficulty.) A D-T fuel cycle is not accompanied by any excess neutrons at all, while the D-D cycle produces one neutron for three deuterons burned. By utilizing side reactions, the D-T cycle can achieve some excess neutrons--also available to PACER--leaving, however, at least a fourfold advantage in materials production potential in favor of the D-D cycle used by PACER. The important breeding advantages of PACER are therefore not available to its competitors--at least until the second generation of machines, probably well into the next century.

As mentioned in the section on Safety, approximately 40 Kg of tritium will be produced each year in a PACER cavity. It is not, at present, practical to recover the tritium from a steam filled cavity because an isotope separation would be required. Some PACER cavities could, however, use CO_2 as the working fluid, from which the valuable isotope ^3H might be recoverable.

If techniques for recovery of materials from the power cavity are successful, then a 2000 Mwe power plant could produce approximately 25 Kg of ^{239}Pu or ^{233}U per day, if half the excess neutrons are captured in fertile material. Such an abundance of fuel would make the construction of expensive conventional breeder reactors unnecessary. The readily available ^{233}U or ^{239}Pu could be used, if desired, to fuel inexpensive, efficient burner reactors, leaving all the "breeding" to PACER facilities. A single PACER cavity could supply material for eight such reactors each operating at 1000 Mwe average power. A comparison of PACER and the LMFBR as breeders is shown in Figure 2. Although this aspect of PACER has so far received little attention because of limited funds, it could be extremely important in providing the maximum increase in nuclear generating

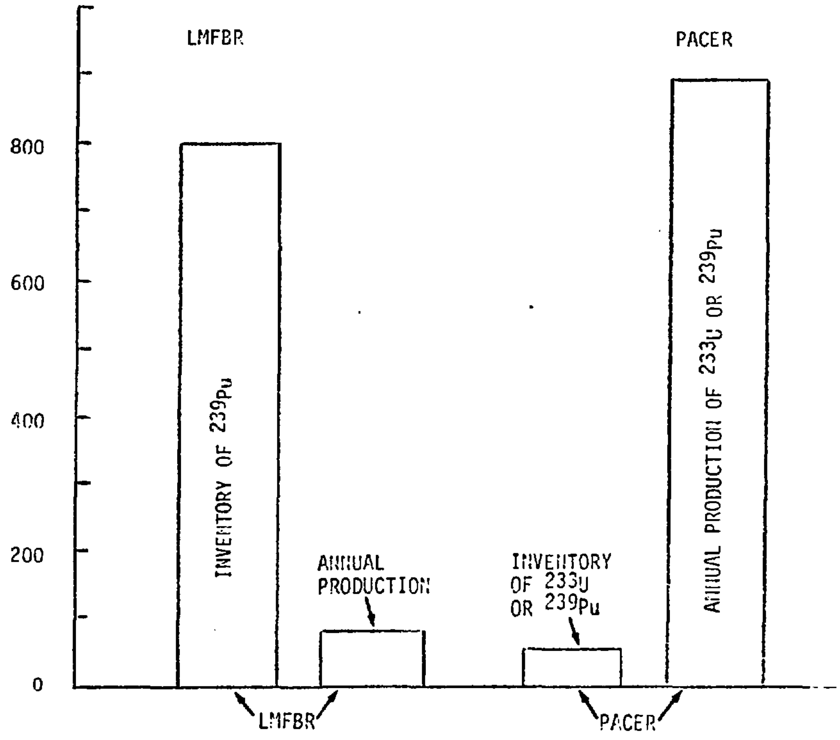

FIGURE 2. COMPARISON OF LMFBR AND PACER AS BREEDERS,
EACH TYPE SUPPLYING 200 Gw(e); i.e., HALF THE 1974 U. S. CAPACITY
(VALUES ARE IN METRIC TONS.)

capacity at the earliest date. It is worth noting that remote location of PACER plants is not a disadvantage if they are operating primarily in a fuel production mode.

ADVANTAGES OF THORIUM UTILIZATION

If PACER is used for fissionable material production, then, in our view, there are some persuasive arguments which favor the production of ^{233}U from thorium rather than Pu from uranium. The usual objection that ^{233}U is a hazardous material does not apply here.* PACER produced ^{233}U will, in fact, be many times less hazardous than plutonium.

The main point in favor of the use of ^{233}U in a nuclear power economy is that it greatly reduces the threat of homemade bombs. The ^{233}U can be diluted with natural uranium to the point of non-explosibility, after which an isotope separation would be required in order to build a bomb from this material. On the other hand, the uranium isotope mixture would still be rich enough in ^{233}U to provide a good reactor fuel. The only plutonium then available to a hijacker would be that associated with highly radioactive spent fuel from burner-reactors on its way back to reprocessing. This lethal material is not an attractive target for thieves, but even this could be reduced by purposely designing the burner reactors to be very poor converters.

---

*^{233}U produced in PACER is free of the contaminating ^{232}U which gives rise to the troublesome gamma rays. The decay chain of ^{232}U includes high energy gamma ray emitters which makes reactor produced ^{233}U very hazardous to handle. The unwanted ^{232}U arises because a long neutron exposure of the thorium is required in a reactor and some fast neutrons are inevitably present to react with the daughter products of the ^{233}Th. When ^{233}Th is formed in an explosion, the capturing blanket disappears into very small particles at extremely low concentration. This, coupled with the short slowing down length for neutrons in the steam, insures that the 232 chain is not formed, and the final product ^{233}U has no hazardous contamination.

Finally, it should be pointed out that U.S. thorium reserves are at least as large as uranium reserves [8-12], so the utilization of thorium would facilitate the expansion of nuclear power.

ECONOMICS

At this stage of the work, it is not possible to give a complete discussion of the cost of producing power. Although reasonable estimates have been made of the costs of major system elements (see Appendix 2), the cost of producing the fuel charges has not yet been determined. The reason for this is that completely new production facilities must be designed to mass produce the fuel charge. A cost study is being made but is not yet complete.

In order to make some meaningful estimates, we have to base our costs on early AEC published data [7]. These data give the cost of a 50 kT charge as $420,000. We believe that a modernized mass production fuel factory will be able to produce PACER fuel charges at least an order of magnitude cheaper than this. We wish to emphasize that the use of the 1964 cost data would be unjustified, since they are tied to small quantity production through the normal weapon fabrication facilities.

If recovery of nuclear materials is successful, the cost of the fuel charge will be reduced by the value of the unburnt, original fissionable material recovered. We assume this benefit is small compared to the value of material produced, at least for this example. ^{233}U or Pu are assumed to be produced in the amount of 11 Kg per fuel charge, corresponding to capture in fertile material of one half of the excess neutrons. We estimate the capital investment in a recovery plant at about $50 M for one cavity; however, the actual plant would probably be larger serving several cavities in a power complex.

Figure 3 gives a breakdown of the cost of electricity for PACER compared to conventional plants [13]. The estimated 1980 power plant cost used for PACER is ~$900 M. A breakdown is given in Appendix 2.

Figure 4 shows the requirements on cost of the fuel charge if PACER is to compete with conventional systems.

THE DEVELOPMENT PLAN

The proposed program can be broken down into three phases corresponding roughly to laboratory tests, field tests and prototype tests.

Phase I

- Theoretical investigation of all physics and chemistry problems
- Conceptual solution of all engineering design problems
- Fundamental materials creep and rupture and corrosion tests
- Engineering componentry testing as required
- Theoretical and laboratory studies of breeding and recovery
- Preliminary economic and system analysis of burner reactor utilization.

The cost of Phase I for the first three years is approximately $10 million.

Phase II

The object of Phase II is to obtain as much <u>in situ</u> salt dome data as necessary to allow prototype construction to begin. For this purpose, a 10-meter diameter cavity with easy access from a salt mine at ~1000

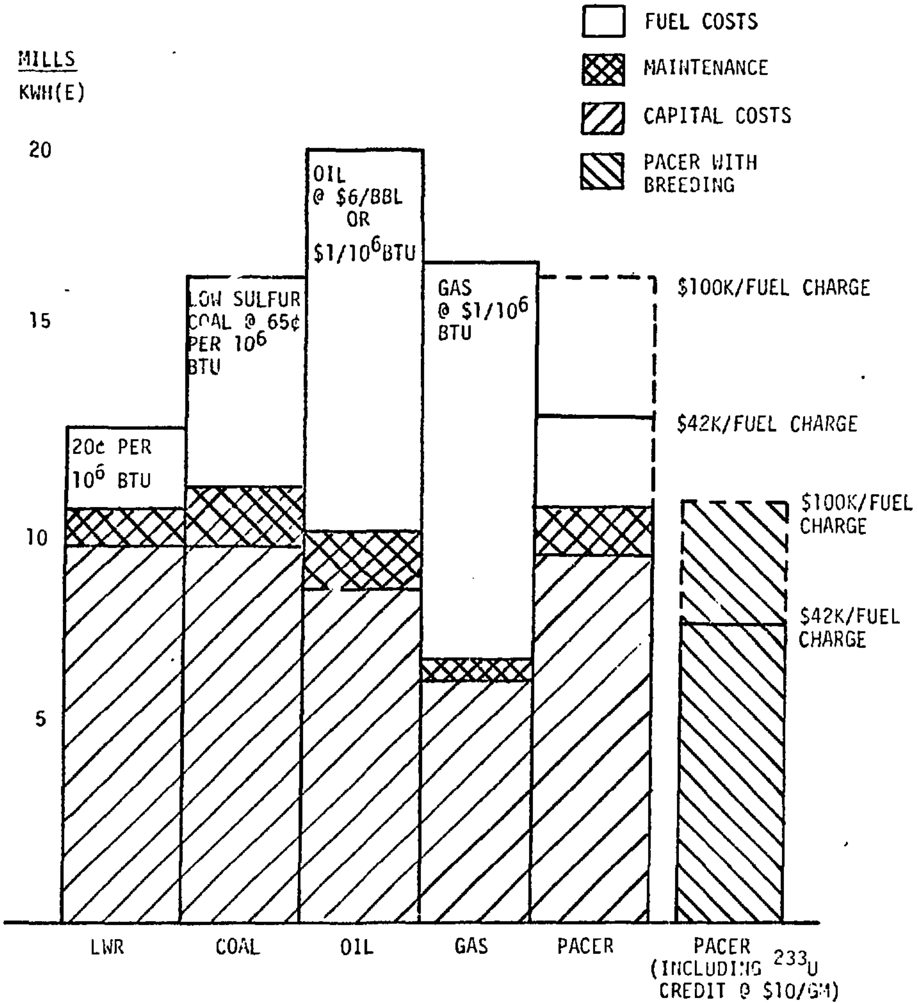

FIGURE 3. ESTIMATED COST OF POWER IN 1980
(80% CAPACITY FACTOR, FIXED CHARGES 15%/YEAR)

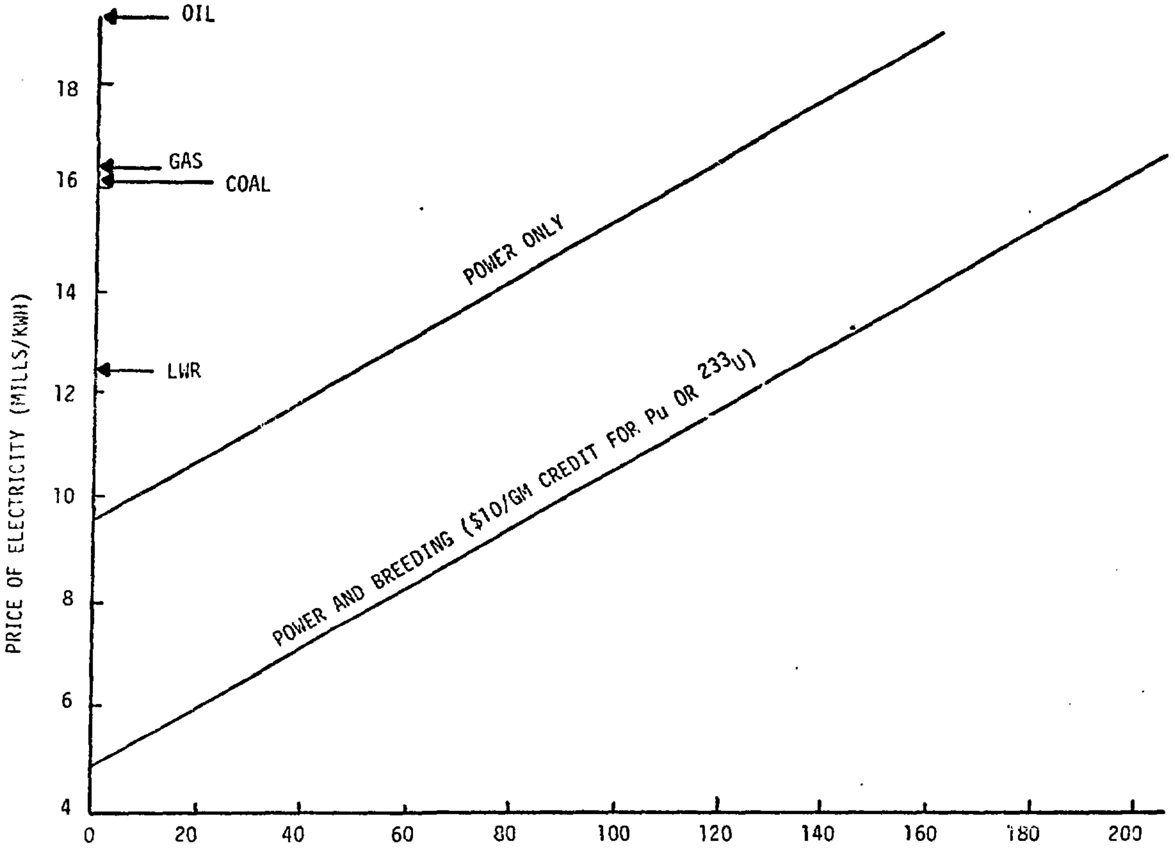

FIGURE 4. COST OF FUEL CHARGE ($10^3)
ESTIMATED 1980 COST OF ELECTRICITY FROM PACER

feet depth will be constructed. Data from the shallow depth are useful because the creep properties of salt are very temperature dependent but less dependent on pressure. Manned access will greatly increase the utility of the cavity and the speed of data acquisition. Hot steam and 1-2 ton chemical explosive tests will be conducted. It is planned to finish these tests in three years at a cost of 2.5 to 3.5 million dollars.

Phase III

The object of Phase III is to obtain the experience required to proceed with a full-scale plant. Four new aspects are added in this phase.

1) Construction of a 100-meter diameter cavity,
2) Explosion of nuclear charges in the cavity,
3) Operation of the facility as a power plant at 10 to 50 Mwe output,
4) Operation of a nuclear materials recovery pilot plant.

It is expected this phase can be completed in 9 to 10 years, if no hitches develop. The cost, without prototype testing, but including one or two nuclear tests is ~\$20 million. One year of prototype testing will cost ~\$100 million, assuming that inexpensive fuel has not yet been developed for that operation.

The above costs are based on experiments and tests in salt domes. If a parallel study of rock cavities is undertaken, the added cost will be roughly 1-1/2 times the above estimates, except for the most expensive item, prototype testing, which should be about the same.

WHAT NEEDS TO BE DONE NOW?

The immediate problems that need to be attacked are, 1) the basic material properties questions at PACER operating conditions; 2) tests on laboratory cavities under operating conditions; 3) planning and start of the engineering development tests on specific components (primary loop, explosive injection mechanism); and 4) site selection and exploration for the 10-meter cavity construction and testing.

The theoretical attack on physics, chemistry and engineering problems is well in hand but needs expanded support for the many engineering design areas which must be worked on, particularly chemical engineering and recovery of materials. Plans have also been made to study the possible use of large cavities in salt domes for repeated nuclear testing. Some of this technology would be identical to PACER.

In order to insure rapid development of PACER, preliminary detailed engineering design work for the prototype should be begun in FY'75 by one of the experienced architect-engineer firms. This will minimize possible later delays due to unanticipated practical problems.

FUNDING

The AEC has funded PACER during the first year at a level of $447,000 with $347,000 from the Division of Military Applications and $100,000 from the Division of Applied Technology. These funds are distributed: $200 K to LASL and $247 K to RDA. The second year funding is presently at a level of $300 K; $50 K at LASL and $250 K at RDA.

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APPENDIX 1

SOME HIGHLIGHTS OF THE FIRST YEAR'S WORK

Detailed study of the explosion phenomenology in the steam filled cavity has shown that:

1) The wall shock is smaller than expected. This will probably reduce seismic effects or allow a somewhat smaller cavity,
2) The hot fireball probably mixes with steam and cools before it can rise to the top, and
3) A mixture of a small amount of air with the steam is sufficient to keep thermal radiation from the cavity walls.

Engineering conceptual design studies have shown that there are no severe costs of materials problems, but have dictated a move to lower working pressure (from 320 to 200 bars). The expected thermal efficiency is ∿30%.

Calculations of salt cavity deformation and rise over a period of years, although not yet completed, indicate it is not a serious problem.

Experiments have begun exposing candidate engineering materials to PACER operating conditions.

Special efforts are underway to envision and explore any possible mechanism which would allow working fluid to escape from the cavity. One such mechanism has been postulated and an experiment has been planned to investigate it.

A study has shown that CO_2 makes an acceptable backup working fluid.

APPENDIX 2

CAPITAL COST* 2000 MW POWER PLANT

200 *20 Bars*
525 50°C
1.2 Km Depth

300 M Diameter
Unlined Cavity
Solution-Salt Dome

	Cost (Million Dollars)
Site selection and testing	10
Cavity and shaft formation	100
Pipes	150
Insertion system	25
Containment system	75
Waste treatment system	15
Site preparation, roads, buildings	25
Heat exchangers	50
Pumps	10
Turbine generators	100
Condensers	20
Piping, auxiliaries, controls	60
Cooling towers	50
Shock isolation	20
Safety, security	10
Engineering, management	50
	770
	385 $/Kwe

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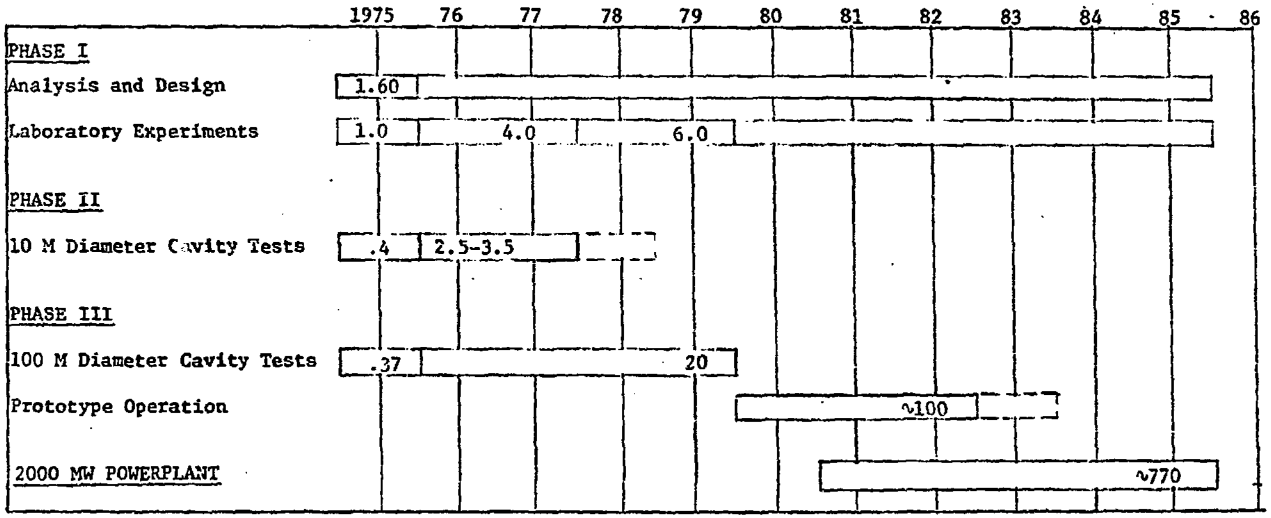
*1973-74 dollars.

APPENDIX 3

PROGRAM SCHEDULE AND COSTS ($M)



Ref. 5

UNIVERSITY OF CALIFORNIA
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(CONTRACT W-7405-ENG-36)
P. O. Box 1663
Los Alamos, New Mexico 87544

IN REPLY
REFER TO: DOS-1-74
(Revised)

November 28, 1973

CONSTRAINTS ON PACER THERMONUCLEAR EXPLOSIVES

Constraints on the design of the PACER thermonuclear device are as follows:

1. Security: Procedures for device manufacture, assembly, and handling must ensure that neither design information nor classified device components can be acquired by unauthorized personnel.

2. Safety: The device must be designed so that it is incapable, under any condition, of producing any nuclear yield prior to the intended time and place of explosion. The probability of destruction or of plutonium contamination through detonation of the device explosive must be remote. The device must also be designed to minimize the consequences of any accidental leakage of working fluid. PACER system design will, of course, make any such malfunction extremely improbable. Safety constraints place a premium on a device design that minimizes fission yield, residual plutonium, and induced radioactivity.

3. Natural Resources: The device should be designed to minimize demands on our natural resources. In particular:

- A minimum amount of SNM should be used.
- Deuterium should be emphasized as the thermonuclear fuel rather than tritium or lithium. Lavish use of tritium should be avoided, particularly if there is no practical way of recovery of generated tritium from a water working fluid. Lithium is impractical in the long run since, in terms of energy units, its supply is about as limited as that of fossil fuel.

4. Breeding: There will be a need for breeding plutonium and possibly tritium. A device designed to optimize plutonium breeding should use deuterium as a thermonuclear fuel to maximize neutron production. This simply emphasizes a previous requirement for the use of deuterium in preference to other fuels. Though there are some possible points of difference between PACER devices designed for breeding and those not so designed, these points are considered minor.

5. Cost: PACER devices must be produced at a cost that permits power production at a rate competitive with other means. The absence, within reason, of restrictions on weight, size, and environmental requirements will help in achieving this goal. However, to minimize cost under the constraints mentioned above will require an imaginative design program based on the latest technology and advanced production practices.

6. Yield: The device yield is expected to be between 10 and 100 kt. With today's technology, higher-yield devices are more cost effective and can be made to produce less radioactive products per kiloton than lower-yield devices. For this reason, early PACER studies have focused on a 100-kt thermonuclear energy source. On the other hand, a lower-yield device, say 10 kt, allows a tenfold reduction in cavity volume and thus reduces concern over cavity stability. It is therefore appropriate to investigate the entire yield range from 10 to 100 kilotons.

The foregoing constraints define the following approach for design of a PACER device:

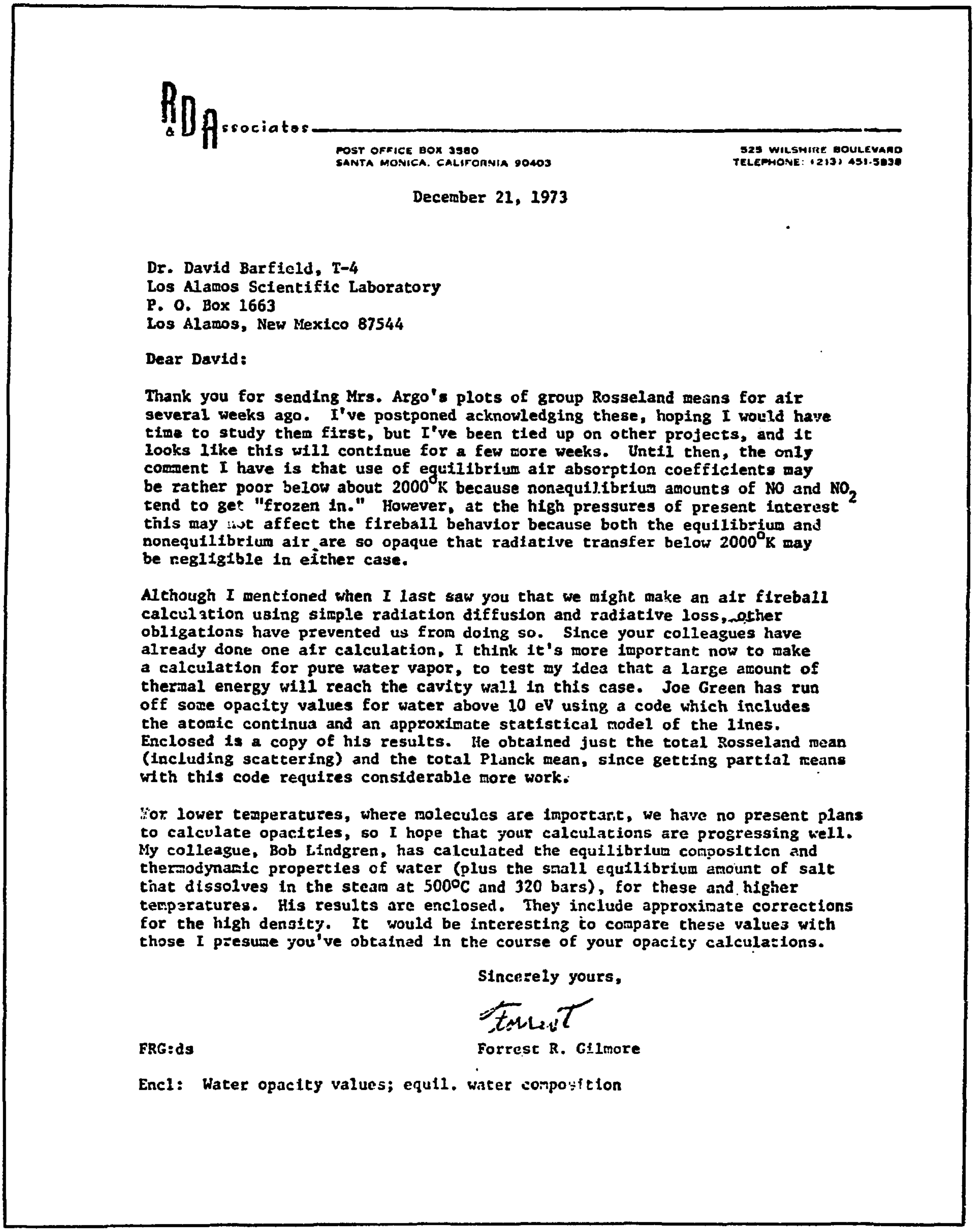
1. Yields from 10 to 100 kt will be investigated.

2. The basic thermonuclear fuel will be deuterium. Use of tritium and lithium should be minimized.

3. Fission yield, SNM usage, and induced activity must be minimized. This goal should be possible since size and weight, within reason, are not restricted.

4. The device design and the procedures associated with its manufacture, assembly, and handling will emphasize security and safety as the main priorities. Under the cited constraints minimum cost is required.

Ref. 10



R&D Associates

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525 WILSHIRE BOULEVARD
TELEPHONE: (213) 451-5838

December 21, 1973

Dr. David Barfield, T-4
Los Alamos Scientific Laboratory
P. O. Box 1663
Los Alamos, New Mexico 87544

Dear David:

Thank you for sending Mrs. Argo's plots of group Rosseland means for air several weeks ago. I've postponed acknowledging these, hoping I would have time to study them first, but I've been tied up on other projects, and it looks like this will continue for a few more weeks. Until then, the only comment I have is that use of equilibrium air absorption coefficients may be rather poor below about 2000°K because nonequilibrium amounts of NO and NO_2 tend to get "frozen in." However, at the high pressures of present interest this may not affect the fireball behavior because both the equilibrium and nonequilibrium air are so opaque that radiative transfer below 2000°K may be negligible in either case.

Although I mentioned when I last saw you that we might make an air fireball calculation using simple radiation diffusion and radiative loss, other obligations have prevented us from doing so. Since your colleagues have already done one air calculation, I think it's more important now to make a calculation for pure water vapor, to test my idea that a large amount of thermal energy will reach the cavity wall in this case. Joe Green has run off some opacity values for water above 10 eV using a code which includes the atomic continua and an approximate statistical model of the lines. Enclosed is a copy of his results. He obtained just the total Rosseland mean (including scattering) and the total Planck mean, since getting partial means with this code requires considerable more work.

For lower temperatures, where molecules are important, we have no present plans to calculate opacities, so I hope that your calculations are progressing well. My colleague, Bob Lindgren, has calculated the equilibrium composition and thermodynamic properties of water (plus the small equilibrium amount of salt that dissolves in the steam at 500°C and 320 bars), for these and higher temperatures. His results are enclosed. They include approximate corrections for the high density. It would be interesting to compare these values with those I presume you've obtained in the course of your opacity calculations.

Sincerely yours,

Forrest R. Gilmore

FRG:ds

Encl: Water opacity values; equil. water composition

Ref. 11

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IN REPLY REFER TO: T-4

January 7, 1974

Dr. Forrest R. Gilmore
R & D Associates
Post Office Box 3580
Santa Monica, California 90403

Dear Dr. Gilmore:

Thank you for your letter of December 21 and enclosed H_2O - NaCl chemistry results. Comparison with similar results for pure H_2O obtained by Dexter Sutherland (J-10) indicates that the small amount of NaCl has a large effect on the electron concentration at 5000 °K, perhaps not an unexpected result. We will make further comparisons. Can you furnish a reference for free-energy data for Na and Cl things?

I have shown the high temperature "water" opacities which you sent to Al Merts.

I added H_2O infrared absorption coefficients to the ABSCO code using an approximate model due to Thomson, Penner and Varanasi (for $1 \text{ atm} < P_{H_2O}$) and Auman's data published in A.J. (for low pressure range). We hope to receive data from AFWL this month for contribution of vibration-rotation bands of NO.

We received some virial coefficients for H_2O in the temperature range 2600 - 3900 °K from T. Spurling, Commonwealth Scientific and Industrial Research Organisation (Australia). Dexter Sutherland derived some values for second and third virials by fitting handbook data (Landolt-Börnstein) for temperatures < 850 °C. Enclosed is a copy of Dexter's curves which also include Spurling's values.

Sincerely,

David Barfield

DB/mw
encl: as cited
cc: W. Huebner, T-4
A. Merts, T-4
R. Shreffler, DOS-1
C. D. Sutherland, J-10

P.S. We will be happy to send H_2O absorption coefficients if you have use for them. Give me a call and let me know what form you would like to have them in.

Ref. 12

LOS ALAMOS SCIENTIFIC LABORATORY
UNIVERSITY OF CALIFORNIA
LOS ALAMOS, NEW MEXICO 87544

OFFICE MEMORANDUM

TO : R. G. Shreffler, DOS

DATE: February 13, 1974

FROM : W. D. Barfield, T-4

SUBJECT : PACER Phase 1 Report

SYMBOL : T-4

1. Some important uncertainties relevant for RADFLO calculations are: a) The equation of state of H_2O is not known for the regime $1000°C < T < 3000°C$ at high P. We are working on a semi-empirical equation of state, making use of virial coefficients supplied by T. Spurling(1) (2600-3900°C) and published compressibility data ($T \leq 900°C$, $1 \leq P \leq 6000$ bar, 25000 bar $\leq P \leq 250000$ bar).(2) b) There is some evidence(3)--not conclusive--that H_2O is highly dimerized at pressures greater than 100 bar and low temperatures 400-1000°C (?). If this is the case, the absorption coefficient would be expected to be qualitatively different from that of the monomer. Measurements of the integrated band strengths would be required, if the bands are non-overlapping. In the case of overlapping bands, measurements of absorption spectra at all temperatures and pressures of interest (where there is a significant abundance of dimers) would be required. It is possible that ab initio calculations of oscillator strengths for the dimer could also be helpful, although at the present time such calculations for polyatomics are expensive, not straightforward, and may give only order of magnitude accuracy. Experimental spectra should be taken for several temperature-pressure combinations of interest, in any case.

2. A background reference which might be useful for Task 2.4 is Ref. (4) below. Isn't the question of wall integrity-stability following repeated shock loading an important one for investigation?

3. Recent progress toward Task 2.2 goals: a) The AFCRL atlas of water vapor (monomer!) lines has been received from NMSU and converted for the LASL 7600. b) A new version of ABSCO (AFWL absorption coefficient code) with line-broadening capability has been converted for the LASL 7600 and tested. It will be used with AFCRL tape above to improve H_2O vapor IR absorption coefficient values. c) A new atlas of atomic lines (neutral N and O and ions) has been constructed using data received from Lockheed. The new atlas is

more complete (25000 lines) than the one in use to date and has line-broadening parameters. d) New molecular band atlas tapes have been received from AFWL and are being incorporated in ABSCO. Included are the IR vibration-rotation bands of NO.

W. D. Barfield

WDB/mw

References

(1)Letter from T. Spurling, 12/20/73.

(2)Holser and Kennedy, Am. J. Sci. 257, 71 (1959); Maier and Franck (1967), quoted in Landolt-Börnstein Tabellen; Rice and Walsh, J. Chem. Phys. 26, 824 (1957).

(3)Yuknevich and Vetrov, Opt. Spectrosc. 34, 387 (1973) (ref. courtesy of L. Jones, CNC-4).

(4)W. D. Barfield, "Uncertainties of Equation of State of Explosively-Loaded Rock Salt," I.D.A. Study S-267 (1968) (Includes review of plastic flow measurements, shock compression measurements, and theoretical equations of state for compressed NaCl.)

LOS ALAMOS SCIENTIFIC LABORATORY
UNIVERSITY OF CALIFORNIA
LOS ALAMOS, NEW MEXICO 87544

OFFICE MEMORANDUM

TO :Distribution

DATE: January 14, 1974

FROM :R. G. Shreffler

SUBJECT :RADFLO CALCULATIONS OF PACER CAVITY AND SUPPORTING THEORETICAL AND EXPERIMENTAL PACER EFFORT

SYMBOL : DOS-1-90

In a LASL meeting we decided to make four RADFLO calculations with the cavity filled with

- air only
- air plus a little water
- water only
- water plus a little air.

The first problem has been calculated by J-10; the second is in progress.

Subsequent to this meeting it has become increasingly evident that the latter two calculations are the more significant ones. The absorption coefficient of H_2O as calculated by Auman[1] for the temperature range 1600°K to 4000°K and low pressures where Doppler broadening dominates is used in the ABSCO absorption coefficient code. These data are supplemented in the higher pressure range ($P_{H_2O} \gtrsim 1$ atm) and temperature range from 273°K to 4000°K by absorption coefficient calculations using a simplified model due to Thomson, Penner and Varanasi.[2] There is some question about the use of the Penner-Varanasi model at the highest pressures of interest, but it is felt that results obtained with this model should represent a worst case analysis. Comparison with measurements at 1 atm[3] shows that the simplified model gives good agreement at the peaks of the absorption coefficient for temperatures up to 3000°K, but substantially lower values in the valleys between the peaks. Data for H_2O lines for wavelengths greater than 1 micron have been received from AFCRL/NMSU. It will be some weeks before these data are incorporated into the ABSCO code with appropriate line broadening. Data on NO vibration-rotation bands may be received from AFWL shortly.

The following specific programs have been or will be carried out:

T-4[4]

1. David Barfield has added the Penner-Varanasi approximation for absorption by water to the molecular absorption coefficient code (ABSCO). This will supplement Auman's data.[1]

2. Chemistry will be checked out and if necessary improved (in particular combinations of N, O, and H). Results received from Gilmore[5] indicate that it may be necessary to add species formed from Na and Cl. The small amount of NaCl in the equilibrium mixture appears to have a large effect on the electron concentration at 5000°K, for example, which would affect the contribution of free-free processes to the absorption coefficient. (It isn't clear at this point whether the free-free contribution is important--compared to absorption by NO and H_2O in the IR--in this temperature range.)

3. Preliminary data will be transmitted to J-10.

✓4. NO vibration bands[6] will be added to ABSCO if received from AFWL.

/5. Line broadening will be added to ABSCO.

/6. A water vapor line atlas will be added when the data are obtained from Beebe (New Mexico State) and McClatchey (AFCRL).

/7. An equation of state for water will be acquired. David Barfield has contacted Dr. T. H. Spurling (Australia) for their data. Spurling has responsed with virial calculations.[7]

J-10

1. An initial calculation with dry air in a cavity of 193 meters radius and 500°C, 440 atm ambient pressure and temperature has been carried out.

2. A second calculation with air plus a small fraction of water in a cavity of 193 meters radius and 525°C, 320 atm will be carried out.

3. Subsequent calculations will be directed toward an ultimate investigation of water with a proper amount of NaCl and with a minimum amount of air for adequate absorption.

CNC-4

1. Llewellyn Jones will define the laboratory experiments which can be done in support of opacity calculations. Emphasis will be placed on the discovery of increments in wavelength that are not absorbed by the working fluid.[8]

REFERENCES

1. J. Aumen, Jr., "The Infrared Opacity of Hot Water Vapor," Astrophysical Journal Supplement, Vol. 14, p. 171, 1967. The temperature range reported extends from 1600° to 4000°K; the densities are very low.
2. S.S. Penner, P. Varanasi, "Approximate Band Absorption and Total Emissivity Calculations for H_2O," JQSRT, Vol. 5, pp 391-401, 1965. This article presents a simplified procedure for temperatures up to 2000°C. Good agreement was obtained with experimental data taken up to pressures of 15 atmospheres.
3. Ludwig, Appl. Optics 10, 1057, 1971.
4. W. F. Huebner to R. G. Shreffler, "Priorities in Opacity Computations for PACER," October 16, 1973.
5. F. Gilmore to D. Barfield, December 21, 1973.
6. NO bands are prominent in the infrared. NO_2 bands, prominent in the optical and ultraviolet, are already in the subroutine of ABSCO.
7. D. Barfield to F. Gilmore, January 7, 1974.
8. International Critical Tables, Vol. 5, pps 327-329. Tabulate some data on absorption by $NaCl$-H_2O solutions.

R. G. Shreffler

RGS:rb

Distribution:
D. P. MacDougall, ADW
C. I. Browne, J DO
Milton Peek/John Zinn/John Kodis, J-10
P. A. Carruthers, T DO
Jack Barnes/Walter Huebner, T-4
David Barfield, T-4
G. A. Cowan, CNC DO
R .Penneman, CNC-4
Llewellyn Jones, CNC-4
Harmon Hubbard/F. Gilmore, RDA
Capt. Richard Harris, AFWL/DYT
ISD-5
DOS File

Ref. 15

LOS ALAMOS SCIENTIFIC LABORATORY
UNIVERSITY OF CALIFORNIA
LOS ALAMOS, NEW MEXICO 87544

OFFICE MEMORANDUM

TO : R. G. Shreffler - DOS-1

DATE: February 26, 1974

FROM : Llewellyn H. Jones

SUBJECT : Pacer: Experiments on Opacity of Water

SYMBOL : CNC-4

This memo is to summarize my comments at the February 22nd meeting and the subsequent conclusions reached by Forrest Gilmore and myself.

We have the capability of studying the absorption spectrum of the working fluid (water at up to 600°C and 400 atm) in the spectral region 0.19 µm (6.5 ev) to 22 µm (0.06 ev), or perhaps further if suitable windows can be found. This is summarized in the table. Short path lengths (0.1 m) would do for most of the region. However, for 0.35 µm to 1 µm a long path length is necessary. Thus, my suggestion was a 2 meter path length as shown in the figure. To go to much longer path lengths one must consider some elaborate (and expensive) set up, such as a very long cell and a tunable dye laser as a source at one end with a detector at the other.

The working fluid of water at 500 - 600°C and 300 - 400 atm pressure is expected to be highly associated, as indicated by the work of Yukhnevich and Vetrov, (1). Thus we expect the absorption spectrum to be something between liquid water and water vapor at room temperature. Therefore, it is most probable that for a 2 meter path we will see no absorption from 0.45 to 0.6 µm unless a significant amount of NO_2 or other colored gas is present (from air or other sources).

In view of the expense of the experiment, Forrest Gilmore feels that it should not be done. I agree with him unless someone feels that there is a need for accurate absorption coefficients over the spectral region where the working fluid absorbs appreciably. I shall pursue the matter no further unless I hear to the contrary.

It seems to me that one could guarantee opacity by adding a relatively small amount of some colored vapor, such as iodine or nitrogen dioxide.

---

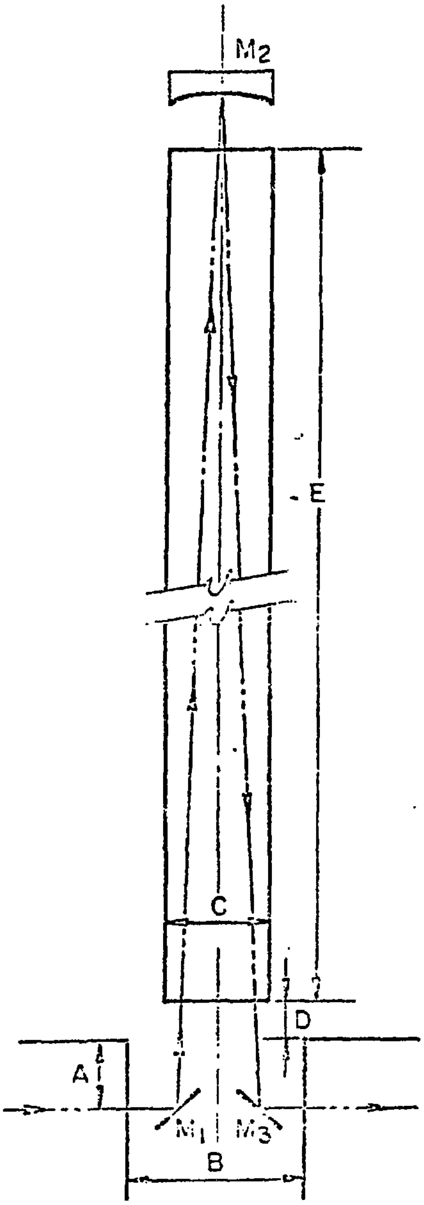
(1) G. V. Yukhnevich and A. A. Vetrov, Opt. Spektrosk. 34, 672 (3).

Llewellyn H. Jones

enc a/s

LHJ rc

RANGE				
µM	0.19-2.	2-5.5	2-22	22-300
EV	6.5-0.62	0.62-0.23	0.62-0.056	0.056-0.004
PATH	2 M	0.1 M	0.1 M	0.1 M
WINDOWS	SAPPHIRE		ZN SE	?



T < 870 K

P < 40 MPa
(400 atm)

WINDOWS: SAPPHIRE

RANGE: 0.19 μm - 2 μm
6.5 eV - 0.62 eV

F/8 OPTICS

RESOLUTION: ~1/1000

A = 0.085 m
B = 0.133 m
C = 0.076 m
D = 0.05 m
E = 1 m

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Ref. 16

LOS ALAMOS SCIENTIFIC LABORATORY
UNIVERSITY OF CALIFORNIA
LOS ALAMOS, NEW MEXICO 87544

OFFICE MEMORANDUM

TO : R. G. Shreffler, DOS-1 DATE: March 1, 1974

FROM : David Barfield

SUBJECT : COMMENTS ON L. JONES' MEMO

SYMBOL : T-4

1. Measurement of the infrared absorption coefficient of pure water vapor at PACER ambient conditions made with 1 meter path length would give information about whether the spectrum looks like that of H_2O monomer, or some more clustered form of H_2O. It would also provide a needed check on our methods for theoretical extrapolation of the absorption coefficient to high pressures (if there is not significant clustering). Measurements at lower (50, 100, 200 atm) and higher pressures and higher temperatures would also be useful for this purpose. Measurements of widths of selected individual lines would also be useful, if Jones has the necessary resolution. (See also my memo dated February 13.)

2. There is nearly an order of magnitude uncertainty in the absorption coefficient of NO_2 at temperatures of about 1000 °K and higher. Compare the points marked "ABSCO 1335 °K", based on emission measurements by Paulsen, with the absorption data (graph attached). Measurements of the NO_2 absorption coefficient could be made at $P = 1$ atm using a small absorption cell (path length ~2 cm). Alternatively, the absorption coefficient of <u>air</u> at temperatures ~800 °K and higher, pressure ~400 atm, could be measured using a one meter path length. (NO_2 is the only important contributor to the opacity of dry air between 1.2 and 5 eV at 1000 °K.) Note that at a concentration $[NO_2] = 2 \times 10^{16}/cm^3$, corresponding to a partial air pressure of ~50 atm at 1000 °K, an NO_2 absorption coefficient = 10^3 cm^2/g corresponds to an absorption mean free path of ~7 m.

3. To my knowledge the absorption coefficient of NaCl and Na_2Cl_2 vapors and some dissociation products (e.g., NaOH) of the NaCl - H_2O system are not known. It might be that one or more of these species would contribute significantly to absorption in the visible.

$$\lambda = \frac{1}{\kappa\rho} = \frac{1}{10^3 \times \frac{2\times10^{16}}{6\times10^{23}} \times 46} = \frac{10^3}{1.5} \cong 7 \text{ meters}$$

4. Although I have not yet had time to check them out, there are probably other measurements useful for the air and molecular opacity programs that could be made with the apparatus contemplated by Jones, especially if he had the capability of going to higher temperatures.

David Barfield

DB/mw
cc: W. F. Huebner, T-4
    L. Jones, CNC-4
Attachment: 1

Reference:

D. E. Paulsen, et al., J. Chem. Phys. 53, 647 (1970).

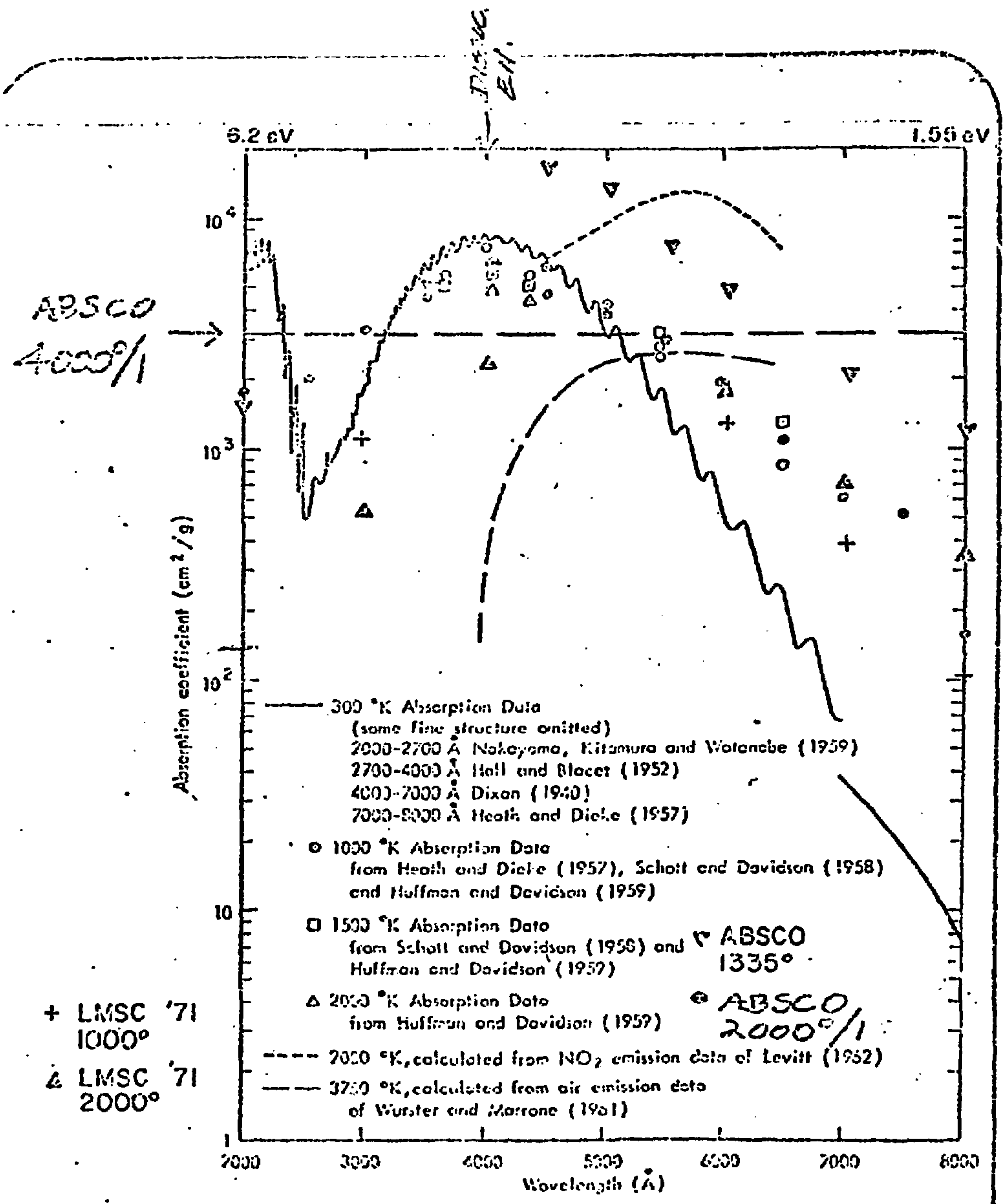

FIG. 4. Absorption coefficient of NO₂.

Ref. 17

LOS ALAMOS SCIENTIFIC LABORATORY
UNIVERSITY OF CALIFORNIA
LOS ALAMOS, NEW MEXICO 87544

OFFICE MEMORANDUM

TO : R. G. Shreffler, DIR-O MS120 DATE: March 1, 1974

FROM : J. Zinn, J-10 MS664

SUBJECT : Pacer - Experiments on Opacity of Water-NaCl System

SYMBOL : J-10

Since a necessary condition for feasibility of Pacer is that the working fluid be effectively opaque to UV, visible, and IR radiation, it seems to me that the opacities need to be measured in some fashion. Forrest Gilmore has noted that water vapor by itself (at 600°C and 400 atm) is probably transparent in the visible, but that visible and UV opacities should be enhanced by the presence of salt. Whether the salt would actually make a difference at 600°C is questionable, and an objective of the experiment should be to answer that question.

A major experimental problem seems to be the construction of an absorption cell to stand 600°C and 400 atm. If such a thing could be built in a modest size (~1 m length) with the capability of covering the visible, near IR, and near UV, it could produce useful data. If it was found that the water-NaCl vapor was so transparent in some spectral range that a longer cell would be required for adequate measurement, that information alone would be useful.

JZ:bsa

cc :L.H.Jones,CNC-4 MS346
W.D.Barfield,T-4 MS212

LOS ALAMOS SCIENTIFIC LABORATORY
UNIVERSITY OF CALIFORNIA
LOS ALAMOS, NEW MEXICO 87544

OFFICE MEMORANDUM

TO : R. G. Shreffler - DOS-1 DATE: March 6, 1974

FROM : Llewellyn H. Jones

SUBJECT : Pacer - Expts. on Opacity of Working Fluid

SYMBOL : CNC-4

After reading the March 1 memos of John Zinn and David Barfield, I conclude that there is still interest in knowing the absorption coefficient of water and water-air mixtures. It seems appropriate for me to give a little more detail on what we can hope to do. With a 2 meter path length, as discussed in my memo of February 26th, there is a region in the visible which is likely to show negligible absorption for water at 400 atm and 770 K. However, by reducing the temperature to 670 K but keeping the pressure at 400 atm or more, we could expect to achieve densities of 0.4 g/mℓ or more. This would significantly increase the amount of water in the path to the point where the absorption at the most transparent wavelength (4800 Å) is expected to be about the same as the sensitivity of our measurement (2% absorption) for a 2 meter path.(1) At 770 K one would have to go to significantly higher pressures to achieve the same density of water. My original thoughts were to design the cell for temperatures up to 870 K and pressures up to 400 atm. There is some tradeoff for strength so that one could go to somewhat higher pressures and lower temperatures, or vice versa. To go to both higher temperature and pressure would require heavier construction but may be feasible.

Some surprise has been expressed over the amount of money requested for this experiment. However, the conditions are rather harsh so that special windows and cells are required. Also, since we are interested in long path lengths, a considerable amount of accessory optical equipment must be designed and purchased, or built at LASL. The instrument we have accepts only small cells (ca. 10 cm) without modification. It is not a simple experiment and it would be foolish to do a mediocre job on it. If it were desired to restrict the study to the region 0.19 μm to 2 μm, it may be possible to cut the cost to 60 K and 8 man months of technical help.

Originally I had assumed that salt would not affect the opacity of the working fluid(2) and had not considered including it in the spectral studies. However, it can be included though it may complicate the cell construction and experimental procedure significantly.

Inasmuch as the theory indicates that H^-, O^-, and OH^- ions formed near the fireball (at > 3000 K) will act as strong absorbers in the visible, an experiment to test this would be important. One could perhaps simulate the expected conditions on a small scale to estimate the opacity of the high temperature water - NaCl fluid.

---

1. This is based on data on liquid water at room temperature by G. M. Hale and M. R. Querry, Applied Optics 12, 555 (1973). Admittedly this is a crude extrapolation but appears to be the best available.
2. Artificial sea water shows the same spectral absorption as pure water according to S. A. Sullivan, J. Opt. Soc. Am. 53, 962 (1963). Of course, at 500°C this is not necessarily the case.

Llewellyn H. Jones

LHJ rc

cc - David Barfield - T-4
John Zinn - J-10
Forrest Gilmore, R&D Associates
P. O. Box 3580, Santa Monica, CA 90403

Ref. 19

LOS ALAMOS SCIENTIFIC LABORATORY
UNIVERSITY OF CALIFORNIA
LOS ALAMOS, NEW MEXICO 87544

OFFICE MEMORANDUM

TO : Llewellyn Jones, CNC-4

DATE: April 5, 1974

FROM : R. G. Shreffler

SUBJECT : PACER Experiments

SYMBOL : DOS-1

As you know the decision has been made not to proceed with CNC-4 opacity measurements of the PACER working fluid. This is just one of a long list of issues we must face and resolve in the PACER program. It's always a comfort to know that we have at LASL experts like yourself which permit us to address such difficulties. I appreciate that reaching this conclusion required a considerable amount of time on your part. Thank you very much.

R. G. Shreffler

RGS:rb
cc: R. Penneman
G. Cowan

Ref. 23

UNIVERSITY OF CALIFORNIA
LOS ALAMOS, NEW MEXICO 87544

OFFICE MEMORANDUM

TO : R. G. Shreffler
DATE August 30, 1974

THRU : F. P. Schilling
Fred Schilling

FROM : T. J. Merson

SUBJECT : CONTRIBUTION TO PACER PROGRAM SUMMARY DOCUMENT - PROJECT 3 - ENGINEERING

SYMBOL : ENG-6-370

MAIL STOP : 310

INTRODUCTION - DESCRIPTION OF THE PLANT CONCEPT

Project 3 [1] includes all aspects of the engineering of the proposed power generation concept from the cavity/piping interface to and including the generating turbine. The explosive device injection system design is also included in this project. Inherent in the study and solution of the problems is the interaction with other project considerations in such areas as choice of working fluid, cavity wall stability, environmental problems, safety, and economics.

A schematic of the conceptual design is shown in Figure 3.1. There are three main flow loops in this concept:

- A "primary loop" which includes the cavity, an upcomer steam pipe, a throttle valve, a liquid pump, and downcomer pipe to return fluid to the cavity.
- A presurrized water "circulating loop", which is actually a subsystem of the primary loop and mixes with steam from the primary loop. This loop accomplishes several functions:
  - a. It increases the mass velocity in the heat exchanger for more efficient heat transfer.
  - b. Circulating water can be controlled to match the pressure and temperature associated with conventional PWR nuclear primary loop conditions.
- A "turbine loop" which circulates noncontaminated fluid through a steam generation plant similar to that used for a PWR nuclear generating station.

The state point conditions [2] for each of the flow loops are indicated for the nominal cavity conditions of 550°C and 33 MPa (330 bars). This set of state conditions is consistent with the assumption that 2000 MWe is produced from a generating plant operating at 30% efficiency. Current technology for PWR generating plants is nearer 35% efficiency [3] which would yield 2345 MWe for the indicated flow rates and temperatures.

An artist's concept of PACER is shown in Figure 3.2. The features included in this sketch are:

- A concrete containment building to house the entire primary and circulating loops and the primary heat exchangers. The fluid in the primary and circulating loops will contain radioactive material from the cavity [4] and the containment building provides a standard means of preventing any leakage from a ruptured pipe from escaping into the environment. The concrete building also acts as a biological shield. The upcomer pipes enter the floor of the containment building so that any seepage along the pipe walls from the cavity can be processed by the containment building gas cleanup system. A modular approach to the design is shown such that routine maintenance of heat exchangers and pumps does not shut down the entire plant.

- Filters are indicated for salt removal or removal of the particulate matter. This could be the point where U^{233} or Pu^{239} could be removed from the primary loop for further processing. The magnitude of the problem depends on the PACER objective (breeding vs. nonbreeding) and could be a major problem introducing complicating factors.

- An overhead remote maintenance capability is provided in the large containment building. Means to transport equipment to a remote assembly and maintenance bay is included. This technology is similar to that developed for the disassembly by remote means of the nuclear rocket engines of the NERVA and Rover Projects.

- The steam turbines, feedwater pumps and reheaters of the turbine loop are not contaminated with radioactivity and hence are housed in a conventional turbine building. The turbines are mounted on helical spring foundations to isolate them from seismic loads [5].

- The device injection system is contained in a separate building which houses the control room for the plant and office space. The actual device injection system consists of a pressure lock and elevator mechanism for lowering the device by gravity through the access shaft to the cavity. The operations in the cavity injection room can be done remotely if necessary. It is anticipated that some radioactive steam will be released from the pressure lock with each charge cycle, but this volume is small and can be handled by a simple gas cleanup system.

- The cooling towers will be required to dissipate large quantities of waste heat. A natural draft tower is shown, but other methods should be considered based on availability of cooling water and economics. This plant concept points up several problem areas that will require further study during Phase I of the PACER study.

TASK 3.1 - TRADE STUDIES

During the course of defining the PACER system, choices between competing design possibilities will need to be analyzed and choices made based on the effect on the total system. The objective of this task is to eventually develop a systems model which will factor the effect of a change in one parameter, e.g., cavity pressure, pipe material, or working fluid, to determine the change in overall plant cost, cycle efficiency, and reliability.

During the preliminary phase of the study, scoping studies of several design questions were performed. One study [6] looks at the effect of cavity pressure and temperature on the efficiency of pressurized water systems with comparisons of the simple Rankine cycle and regenerative and superheated options. Another study [7] discusses the relative cost of cavity access piping as a function of pressure and points out the advantages in piping costs of a shallow, low pressure cavity. It is generally believed that multiple pipes of small diameter (of the order of 10 in. pipe) are more consistent with current technology than one large (of the order of 40 in. i.d.) pipe for these pressures. Reference 8 does the scoping calculations on number, size, and weight of such piping systems with the conclusion that the steam must be condensed before reinjection into the cavity.

Another question that has received attention in the preliminary phase of the study is the choice of working fluid and its effect on overall plant performance. Air [9] and CO_2 [10] have been studied with the conclusion that the pumping power to reinject a gas into the cavity is prohibitive; however, CO_2 can be condensed and its relative chemical neutrality toward salt and pipes makes it worth further study in spite of its capital cost. Argon and hydrogen were considered [11] and pumping power calculated. Using the cavity pressure and a throttle valve [12] still appears to be the best way to get the steam from the cavity to the heat exchangers.

Consideration was given early to using a gas turbine Brayton cycle [13], but the conclusion is that the operation temperatures were too low to provide efficient plant performance.

The effects of cavity size, steam conditions, and device yield on the pressure and temperature swings in the cavity have been studied [14] and the resulting map is shown in Figure 3.3. It is seen that for a 400-meter cavity diameter, the nominal state points from Figure 3.1, and a 420 TJ (100 kiloton) device (corresponding to an increase in specific energy, u, of 109 kJ/kg), the pressure rise is 3.2 MPa (32 bars) and the temperature rise is 44°C.

Figure 3.4 shows the effect of primary loop water return temperature and cavity extraction temperature on the flow in the primary loop. An additional constraint that has been imposed on the cavity state points is illustrated in Figure 3.5. It is assumed that the entire cavity fluid cycle must be to the right of the "saturation line" to prevent the steam from dissolving the cavity wall salt. Since reinjection involves water cold enough to dissolve salt, it is assumed that return water can be reinjected as a spray that will mix with the cavity steam and heat before impinging on a salt wall. This problem should be reduced if the cavity pressure is reduced.

The overall economics for the PACER concept is shown in Table I [15]. This table is based on state points different from Figure 1, but it is intended that this will put various system economics in perspective as well as point up areas where careful cost analysis is warranted early in the program.

TASK 3.2 - PRIMARY LOOP

Detailed design of the primary loop depends on decisions and constraints addressed in many other tasks. Preliminary design has concentrated on the use of steam as the working fluid and assuming that the ASME codes would be the minimum constraints. Figure 3.6 shows the general trend of piping costs with increase in cavity pressure [7]. Also included is an indication of the importance of considering a noncondensible working fluid (CO_2 or air). The actual pipe costs are based on particular assumptions which may not be strictly valid, but are useful to illustrate the trend. It is this piping cost consideration that suggests looking at lower cavity pressures. Preliminary sizing of the heat exchangers has been done using PWR technology [16]. Optimization is not yet started and such questions as to the size and number of pipes in the primary loop upcomer have not yet been addressed in detail. Field fabrication, material availability, and sealing problems will have a strong influence in the final proposed design. The need for vibration isolation and shock attenuation in the access pipe and working fluid has been documented [17].

A big question in the PACER concept is that of the physical quantity, chemical composition, and behavior of the salt dissolved in the steam. Figure 3.5 shows that as pressure of the working fluid decreases (in the upcomer pipe and throttle valve) the solution becomes supersaturated. The salt concentration in the primary and circulating loops at steady state should be only a few per cent of the salt concentration of sea water. Reduction of the cavity pressure to make it only slightly in excess of the circulating loop pressure could eliminate the supersaturation problem if one exists. Where this salt appears and how it behaves in the primary loop is the question that is addressed by Experiment 3 [1, 18]. This experiment will provide bench scale checkout of materials corrosion and salt deposition questions. It is expected that this experiment will demonstrate the workability of the pressurized water system.

It is expected that the primary loop engineering and materials problems may hold the key to the ultimate economic viability of the PACER concept.

TASK 3.3 - MATERIALS

A large body of literature is available on material problems in saline water. Unfortunately, many of the properties of the fluid that affect material lifetimes and properties are not known for PACER working conditions. A discussion of the materials criteria [19] includes the following factors:

1. Effect of salt
    - Corrosion resistance
    - Scale buildup and removal
    - Stress corrosion and cracking
    - Resistance to salts other than NaCl
2. Fabrication
    - Weldability and corrosion of welds
    - Cost
3. Properties
    - Strength at design temperature
    - Ductility
    - Fatigue - low cycle and shock
    - Creep strength
4. Cost and availability

An experiment to answer many of these questions, Experiment 1, [1, 20] is included in PHASE 1 of the PACER program.

TASK 3.4 - CONTAINMENT

Containment of the high pressure working fluid in the cavity and piping systems will be a key consideration in the PACER design. Discussion of containment criteria [21] includes the following points:

1. Containment in the cavity
   - Sealing around the pipe
     - Salt creep
     - Mechanical seal
     - Grout
   - Safety backup
   - QA/QC on installation
   - Startup procedures

2. Containment in the high pressure piping
   - Design to nuclear pressure vessel codes
   - Secondary containment
   - Cleanup system for minor leaks
   - Provide for isolation and replacement of defective hardware
   - Consider T_2 and other problem materials in the working fluid

Much additional effort is called for in defining the problems, documenting potential solutions, and executing laboratory Experiments 4 and 8 [1]. The problem of steam condensing in cool cavity wall cracks and propagating [22] is being investigated in Experiment 7 [1].

TASK 3.5 - DEVICE INJECTION

Device injection incorporates many of the same problems that are present in the primary loop, materials, containment, and cost of high pressure pipes. Early considerations [23] led to several suggested approaches and an attempt to define design criteria [24]. The major areas discussed are Safety, Reliability, Cost, and Design Environment. One suggested approach is shown in Figure 3.2 which consists of a capped high pressure access pipe and a pressure lock near the surface where maintenance is possible. This pipe enters a shielded containment room where remote operation is possible depending on contamination levels.

T. J. Merson
T. J. Merson

TJM:ll

Attachments: References

Cys: R. T. Brasier, ENG-DO MS 310

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TABLE I

CAPITAL COST* 2000 MW POWER PLANT

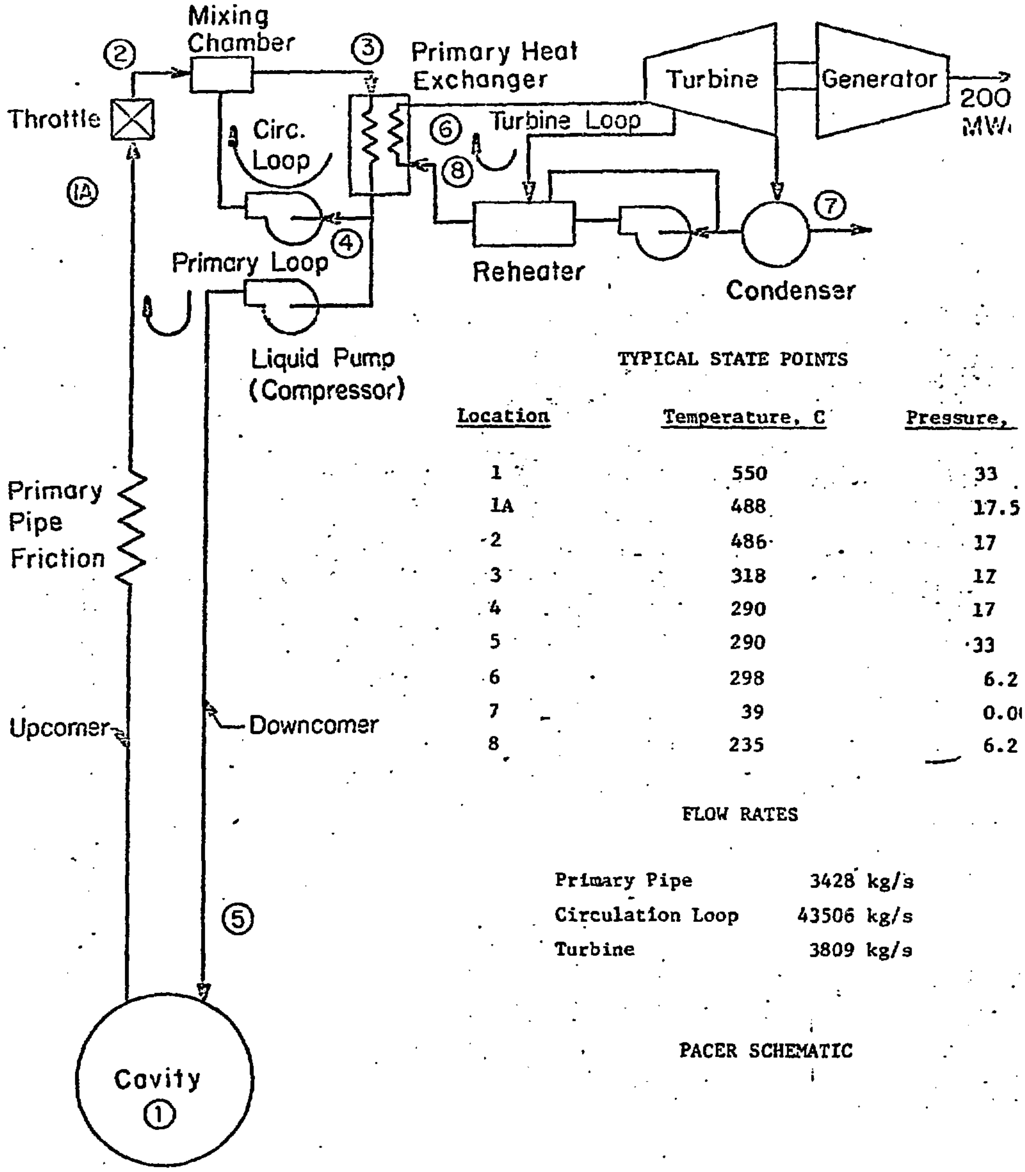
200 ± 20 Bars
525 ± 50°C
1.2 Km Depth
50 kt Yield

300 M Diameter
Unlined Cavity
Solution-Salt Dome

	Cost (Million Dollars)
Site selection and testing	10
Cavity and shaft formation	100
Pipes	150
Insertion system	25
Containment system	75
Waste treatment system	15
Site preparation, roads, buildings	25
Heat exchangers	50
Pumps	10
Turbine generators	100
Condensers	20
Piping, auxiliaries, controls	60
Cooling towers	50
Shock isolation	20
Safety, security	10
Engineering, management	50
	770
	385$/KWe

---

* 1973-74 dollars.



TYPICAL STATE POINTS

Location	Temperature, C	Pressure,
1	550	33
1A	488	17.5
2	486	17
3	318	17
4	290	17
5	290	33
6	298	6.2
7	39	0.0
8	235	6.2

FLOW RATES

Primary Pipe	3428 kg/s
Circulation Loop	43506 kg/s
Turbine	3809 kg/s

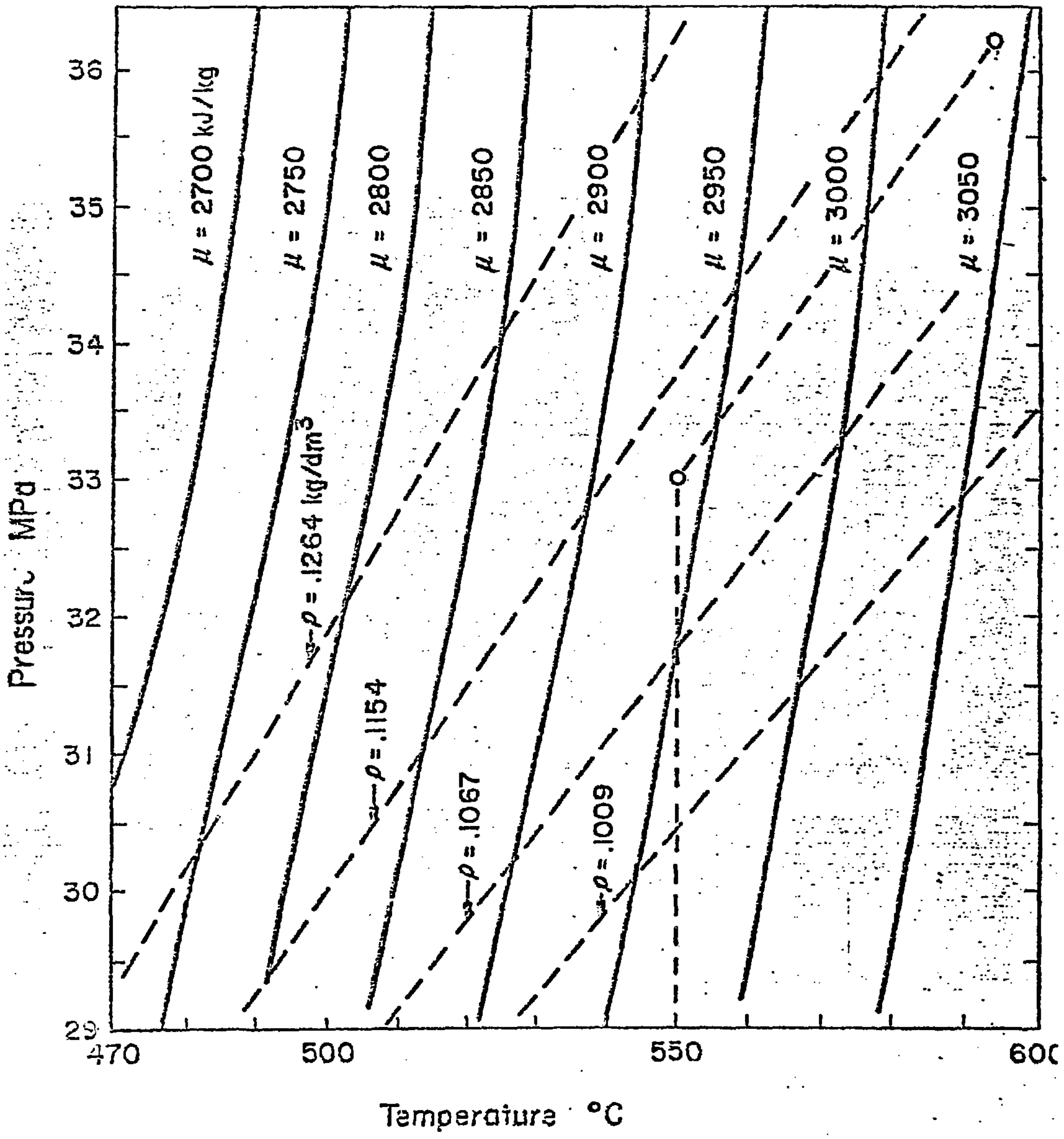
PACER SCHEMATIC

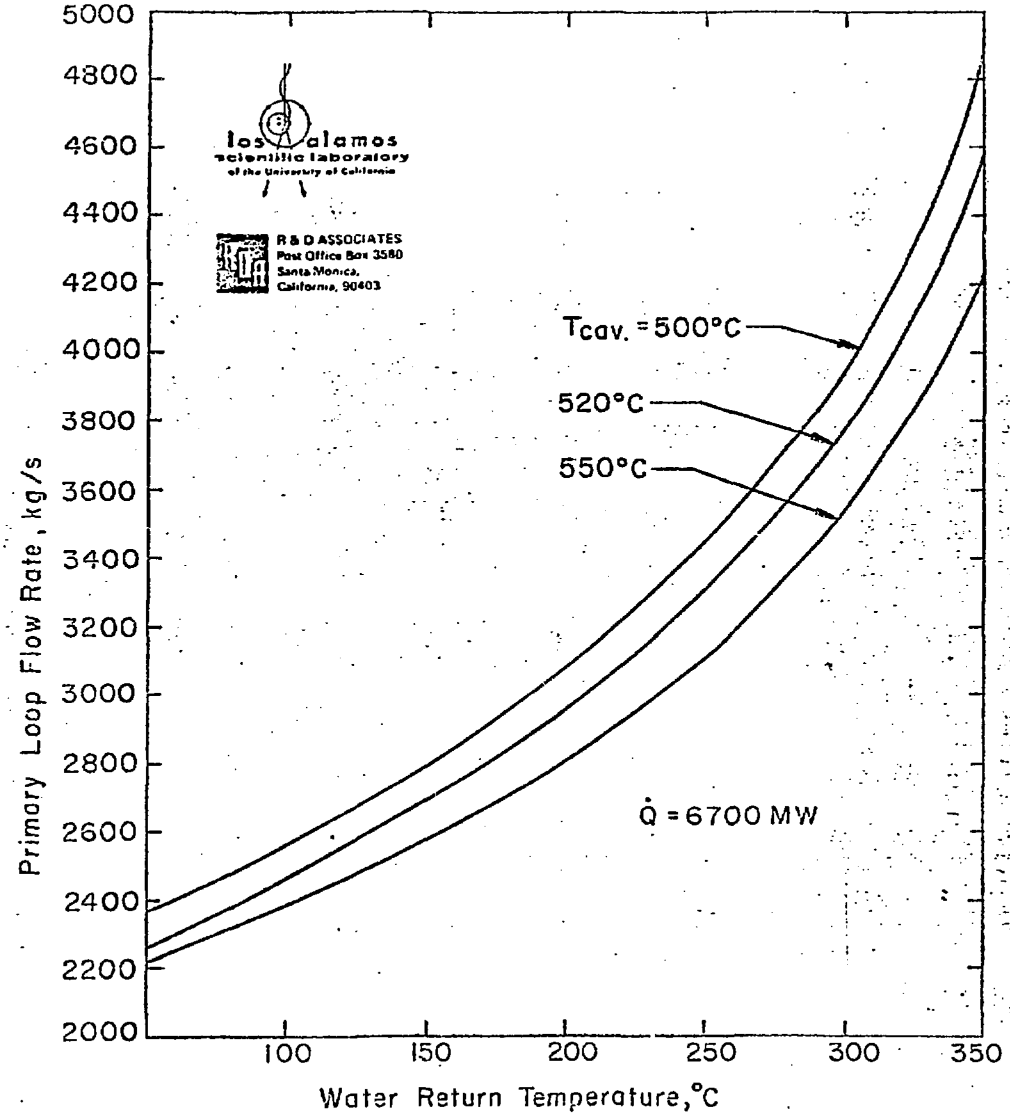
FIGURE 3.2

is a color photograph

LASL ISD-7

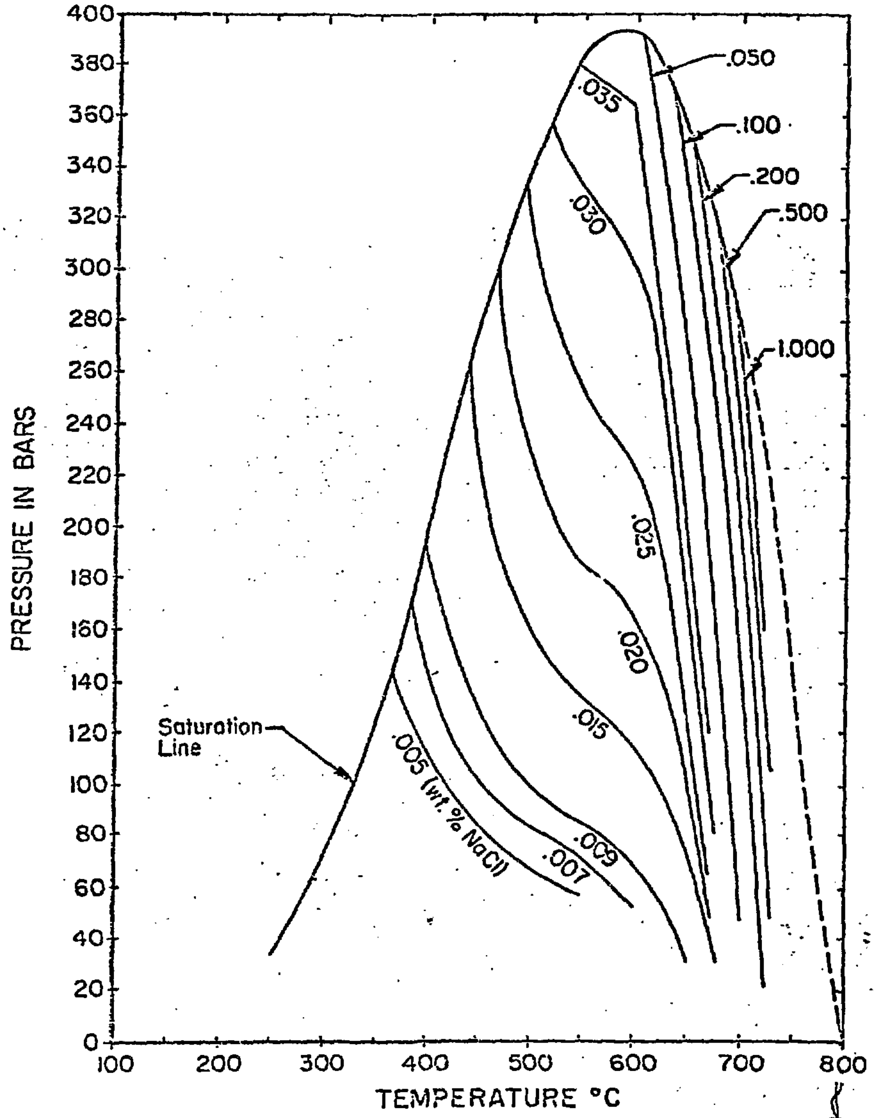
#CN741551


Pressure MPa
36
35
34
33
32
31
30
29
470
500
550
600
Temperature °C
μ = 2700 kJ/kg
μ = 2750
μ = 2800
μ = 2850
μ = 2900
μ = 2950
μ = 3000
μ = 3050
ρ = .1264 kg/dm³
ρ = .1154
ρ = .1067
ρ = .1009



Primary Loop Flow Rate vs Water Return Temperature

Figure 3.4



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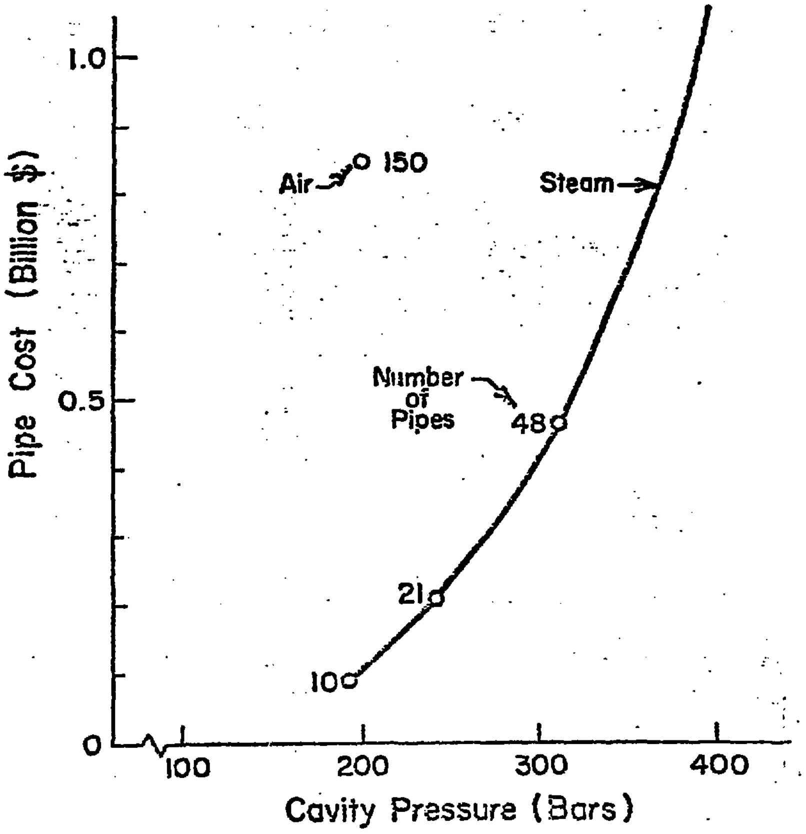
Solubility of Crystalline NaCl in H_2O Gas

los alamos
scientific laboratory
of the University of California

from S. Sourirajan & G. C. Kennedy, excerpted from
American Journal of Science, Vol. 260, Feb., 1962



Estimated Pipe Cost 2000 MW

Ref. 24

LOS ALAMOS SCIENTIFIC LABORATORY
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OFFICE MEMORANDUM

TO : R. G. Shreffler DATE: February [illegible], 1974

THRU : R. E. Roush

FROM : J. J. Koelling

SUBJECT : ENVIRONMENTAL REVIEW - PACER

SYMBOL : ENG-7-2829

As requested by R. E. Roush, I have reviewed the Pacer project for possible environmental or safety hazards with the stipulation that my work be independent of previous studies on the subject. Basically the review was to identify the various project areas that might cause environmental concern either under the guidelines set forth by Public Law 91-190 (National Environmental Policy Act of 1969) or in relation to other considerations that might be or have been emphasized by the anti-nuclear factions.

EPA

In accordance with the National Environmental Policy Act of 1969 and the guidelines established by the Council on Environmental Quality, statements concerning the impact of underground nuclear events on the environment must be submitted to the General Manager, USAEC, prior to the event. The rules governing these statements depend on the yield, type and place of the event. These procedures covering current nuclear tests do not apply to the Pacer concept. In addition, the present-day "reactor" siting criteria as given in 10 CFR 100 do not apply to the Pacer concept. New guidelines concerning environmental statements and "siting" criteria addressing the specialized problems associated with the Pacer concept must be developed.

In general there are two areas that are continually being stressed in environmental or safety reports--seismic effects resulting from ground motion, and radiological hazards. In the case of seismic hazards the problems include (1) direct motion resulting from the detonation and (2) possible triggering of multiple quakes by single or periodic detonations. In the case of radiological hazards the problems include (1) immediate release of event-related radioactivity to the environment, (2) radioactive contamination of the working fluid and (3) diffusion or "seepage" of radioactivity to the environment over a long period of time. These and other associated areas are considered in more detail below.

SEISMIC EFFECTS

There is ample reason not to expect any significant ground motion directly from the relatively low yield devices planned, but the possible triggering of multiple quakes with a single detonation is a serious question, especially in view of the planned multiplicity of detonations. This question will probably be a source of protest with regard to seismic effects. Multiple disturbances on the nuclear-explosion scale and at the same location have never occurred before. Although the mechanisms by which these detonations can trigger an earthquake are not well understood, there is ample evidence that very large quakes consist of a superposition of much smaller events triggered in a certain succession. It has been shown that seismic events in the 6 to 7 magnitude range on the Richter scale can produce aftershocks and slips easily out to 100 kilometers. Also, such relatively small magnitudes have been associated with foreshocks of large earthquakes. Whether or not the periodic detonations planned could develop this level of activity must be determined.

RADIOLOGICAL HAZARDS

Contamination of Ground Water

One of the potential hazards associated with radioactive buildup in the cavity is the contamination of ground water supplies. If the event is near or below the water table, the radionuclides can either affect the water directly or be transported to a more vulnerable site. In general, the biologically significant radionuclides include ^{45}Ca, ^{60}Co, ^{90}Sr, ^{137}Cs, ^{106}Ru, ^{144}Ce, ^{14}C, ^{24}Na, ^{36}Cℓ and ^{3}H. Since transport is very slow and all of these isotopes and their various compounds formed, except for ^{3}H, are strongly sorbed on surfaces, their respective concentrations should fall off rapidly with increasing distance from shot point. Tritium then becomes the predominant nuclide in ground water from a fission-fusion detonation. There are various other nuclides that are transported in addition to ^{3}H but they do not in general create a radiological hazard.

This picture is complicated by the possibly large production of Pu in the cavity, extremely large buildup of ^{3}H in the periodic D-D reactions, and medium change from normal ground materials to salt. The medium change should be beneficial because of the smaller diffusion rate for radionuclides, assuming of course that cavity integrity is maintained.

Cavity Environment

a. Fission Products

The relatively small fission yield associated with each device will lead to only a small quantity of fission products on the individual shot basis. However, the proposed shot rate will result in an ultimate buildup of the longer lived radionuclides. The gaseous fission products (^{85}Kr, ^{131m}Xe, ^{131}I) have high transport rates and can contribute significantly to the radioactivity of the working fluid. Most other fission products formed will be concentrated at the bottom of the cavity.

b. Activation Products

In the salt-steam environment only three products will contribute significantly to the environment activity. These are ^{14}C from the (n, p) reaction in the air, $^{24}\mathrm{Na}$ from the (n, γ) in salt and $^{36}\mathrm{C\ell}$ from the (n, γ) in salt. $^{36}\mathrm{C\ell}$ and $^{14}\mathrm{C}$ are beta emitters and $^{24}\mathrm{Na}$ is a gamma emitter. If any Li is present, the additional reaction $^{6}\mathrm{Li}$ (n, α) $^{3}\mathrm{H}$ can occur which adds to the $^{3}\mathrm{H}$ concentration from the fission process. Activation of any other cavity wall material should be insignificant due to the anticipated density of the steam (0.2 $\mathrm{Mg/m^3}$) and the distance (200 meters) to be traveled by the activating particles. A further reduction in activations of the cavity environment materials can be realized by surrounding the device with boron. This effectively softens the leakage spectrum from the device so that many of the activation cross sections of the target materials are reduced to very low levels.

Fusion Products

In the D-D fusion process there are two competing reactions. They are

$${}^{2}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} \rightarrow {}^{1}_{0}\mathrm{n} + {}^{3}_{2}\mathrm{He} \qquad 48.5\%$$

and

$${}^{2}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} \rightarrow {}^{1}_{1}\mathrm{H} + {}^{3}_{1}\mathrm{H} \qquad 51.5\% \quad .$$

The $^{3}\mathrm{H}$ produced in the proton branch of the reaction can react with the $^{2}\mathrm{H}$ in the D-T reaction,

$${}^{2}_{1}\mathrm{H} + {}^{3}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n} \quad .$$

The $^{3}\mathrm{He}$ formed in the neutron branch of the reaction can react with $^{2}\mathrm{H}$ in the reaction,

$${}^{2}_{1}\mathrm{H} + {}^{3}_{2}\mathrm{He} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{1}_{1}\mathrm{H} \quad .$$

The $^{1}\mathrm{H}$ from this reaction can react with the other products in one of three of the following ways:

$${}^{1}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{2}_{1}\mathrm{H} + {}_{1}e^{0}$$

$${}^{1}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} \rightarrow {}^{3}_{2}\mathrm{He} + \gamma$$

and

$${}^{1}_{1}\mathrm{H} + {}^{3}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + \gamma \quad .$$

With the large fusion yield, buildup of the various reaction products will be substantial due to the low efficiency of the reactions. The exact concentration buildup of these products can be calculated once the fission-fusion ratio is fixed and the detonation rate and efficiency of burn for the device are determined.

Cavity Integrity

The one problem that seems by far the most significant potential environmental or safety hazard is preservation of the cavity integrity throughout its lifetime. Much work has been performed for the sole purpose of minimizing the effect of the device on the cavity wall. .

There appears to be no important problem associated with the direct effect of the device on the wall. By increasing the diameter of the cavity and limiting the size of the device, the displacement and velocity of the wall has been kept well below the point at which damaging stresses can be achieved in the salt. Likewise, with these anticipated small stresses, there should be no chimney formation. As expressed in a previous section, development of unusual stresses in the wall from seismic activity could result in a breach of the wall. This appears the only likely scheme for loss of cavity integrity by fissioning or cracking.

As described in the Cavity Environment section, there is enough potential radioactivity stored in the cavity at all times to create a sizeable environmental hazard should a passage from the cavity to a water region or ground surface be created.

The cavity environment will have a great effect on the design of the heat exchange system, device injection systems, or any other required penetration of the cavity wall. Fortunately a great deal of experience has been gained in Nevada for the design of various components (valves, locks, seals, etc.) for isolating the cavity radioactivity from the outside environment.

If a leak potential does exist, provisions should be made for venting to a secondary containment area. Because of the contamination exposure to the heat exchange-energy extraction systems, these systems will be shielded and fully contained to eliminate the possibility of environmental contamination. This containment structure could act as the secondary containment for any potential leak from the cavity.

Maximum Credible Accident

The maximum credible accident is probably the loss of integrity of the cavity, with the cavity at maximum pressure, after operation over a very long period of time. As in a reactor, reduction of the steam (working fluid) pressure is extremely important. Unless large fissures had been formed, pressure would decrease slowly and seepage would continue for a long period of time depending on the leakage rate.

Allowing the steam to vent to a water-filled reservoir for condensation is a method used in reactor designs to reduce this pressure. In addition, the use of ice beds as a heat sink through which the air-steam mixtures are fed has also been considered. A similar system (using either water or ice) can probably be engineered and designed for the Pacer cavity. Until an accurate determination is made for the building up of fission products, activation products, ^{3}H, etc., radiation doses to the surrounding environment in the event of the maximum credible accident cannot be assessed. It appears possible that, even under the MCA, the dose to the surrounding population would be no greater than that permitted during normal operation.

PLUTONIUM PRODUCTION

One possible alteration of the basic system would allow for the intentional production of large quantities of plutonium^{239}. In that case, the effect on the cavity environment would have to be evaluated in addition to the environmental effects of the plutonium recovery from the cavity. Plutonium recovery could well present the greatest environmental hazard associated with the project.

PUBLIC RELATIONS

It should be stressed that scientific investigations normally carried out for the purpose of satisfying hazard report requirements will in general not satisfy certain factions determined to gain public support for stopping particular as well as general nuclear uses. A thorough public relations job is therefore justified from the very infancy of the project. This holds especially for Pacer, where the proposed salt dome locations eliminate any possibility of secrecy such as that associated with NTS detonations. It is apparent that a proposal for even a single detonation outside the confines of the NTS will be met with great apprehension by the general public.

Another problem in this area arises form previous arguments given in support of other events. In the Cannikin hearings held in 1971 the argument quoted below was used in support of nuclear tests with greater than 1 megaton yield. It is probable that such an argument ~~would~~ be used for the purpose of discrediting the smaller devices. "From 1963 to the end of 1970 there were 225 announced underground nuclear detonations performed in the United States with yields ranging from less than 1 kiloton to more than 1 megaton. In seventeen of the events, all at NTS, measurable amounts of radioactivity were observed off the site. Some observations were from seepage and some from prompt venting. Although none of the radiation levels were in excess of the MPC guidelines of 10 CFR 20 and thirteen of the seventeen detonations were either tunnel or line of sight experiments, the fact remains that fifteen of the yields were less than 20 kilotons and the other two from 20 to 200 kilotons."

J. J. Koelling
ENG-7

JJK/lt
Attach: References

cy: R. I. Brasier
B. J. Donham
F. P. Schilling
T. J. Merson
File

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Ref. 27

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IN REPLY REFER TO: DOS 1

November 29, 1973

Dr. F. Charles Gilbert
Division of Military Application
U. S. Atomic Energy Commission
Washington, D. C. 20545

Dear Chuck:

The attached document has taken a bit longer in preparation than we had expected. Harmon and I hope it serves your purpose. Clearly more work could be done on the association of PACER principles with a new test facility.

We are looking forward to our next visit to Germantown at which time we expect to have the Phase I program reasonably well defined. Phase I includes all paper studies and laboratory experiments which will help in the decision to proceed with nuclear device hardware development and scale experiments with conventional explosives and nuclear devices in salt domes.

Regards,

Bob Shreffler

R. G. Shreffler

RGS:rb
Enc: DOS-1-82: The Association of The Pacer Program and The Nuclear Weapons Program

Distribution:
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DOS-1-82 November 29, 1973

THE ASSOCIATION OF
THE PACER PROGRAM
AND
THE NUCLEAR WEAPONS PROGRAM

Harmon Hubbard, RDA

Robert Shreffler, LASL

INTRODUCTION

During a review of the PACER Program at AEC Headquarters in Germantown on November 5, 1973, it was suggested that a document be prepared to show the association of the PACER Program with the Nuclear Weapons Program. This document responds to that suggestion.

THE PACER PROGRAM

The objective of the PACER Program is best described by referring to Fig. 1, which shows a salt dome in which a large cavity is filled with a working fluid at high temperature and pressure. Thermonuclear devices are periodically detonated within the cavity to elevate the pressure and temperature of the working fluid incrementally. The working fluid is circulated through a heat exchanger where steam is generated to drive a modern conventional steam power plant. Table I presents values for typical parameters defining the system.

We assume for this discussion that such a system will work safely and satisfactorily for 20 years. In achieving this aim a number of goals pertinent to the subject of this paper must be met.

- We must establish high confidence in the durability and stability of the cavity. Of particular interest here is the need to minimize the energy deposited in the cavity walls. In other words, it is important to develop a PACER system in which the explosion is highly "decoupled" from the environment.
- We must develop a modern nuclear device. The bounding constraints and device characteristics are summarized in Annex 1.
- We must demonstrate a primary loop that serves to remove working fluid from the cavity, deposit thermal energy into a secondary loop at or near the surface, and return the spent fluid to the cavity. This loop may have a side loop for chemical processing of the working fluid to remove tritium, plutonium, and any other undesirable substance.
- We must develop a safe and dependable system for quickly translating the thermonuclear device from the surface to the point within the cavity where it will be detonated. Since there is no severe restriction on device size or weight, the injection pipe will probably have a 2- to 3-ft inside diameter.

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CONCEPT DIAGRAM

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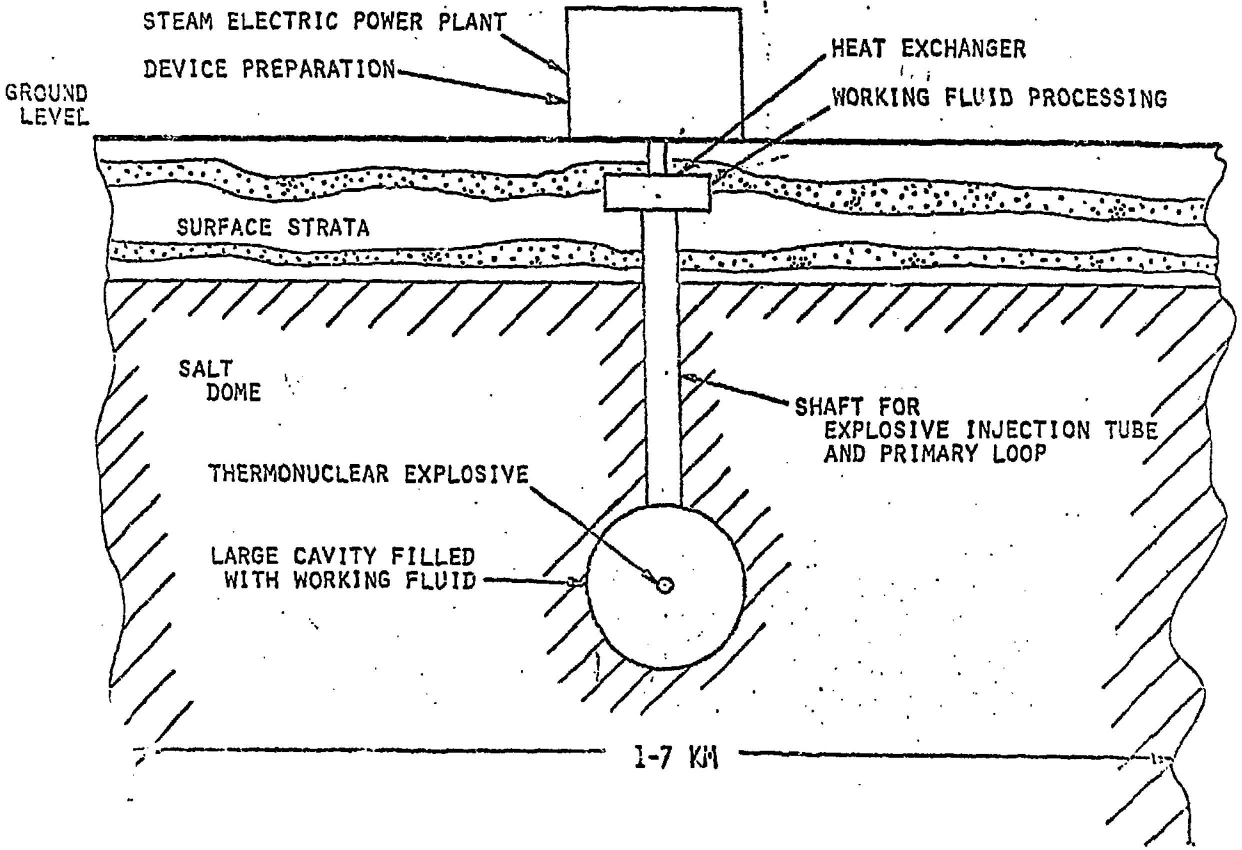

Table I

Typical PACER Parameters

Working Fluid		Water
Ambient temperature:	Minimum	525°C
	Maximum	575°C
Ambient pressure:	Minimum	320 bars
	Maximum	350 bars
Cavity diameter		200 to 400 m
Device yield		10 to 100 kt
Depth of cavity		1500 m
Explosive frequency		1 to 10 per day

THE ASSOCIATION OF PACER AND THE NUCLEAR WEAPONS PROGRAM

The PACER Program and the Nuclear Weapons Program are closely associated in two respects: (1) both programs require nuclear devices, and (2) the PACER system provides the basic requirements for an ideal nuclear-weapons testing facility.

The characteristics of PACER devices outlined in Annex 1, are similar in most respects to those of a nuclear weapon. Similar disciplines are involved for design, development, local and nuclear testing, handling, and production. Specific similarities are associated with device safety and security. The PACER Program places more emphasis on the burning of deuterium as a fuel and on minimizing costs but places little emphasis on reducing size and weight.

Principles of the PACER System could be used in designing a facility (some elements are discussed in Annex 2) intended solely for nuclear-device testing. The advantages over our present methods of underground testing would be significant.

- The safety of the facility would be assured by its existence in a stable homogeneous medium, by a thoroughly understood cavity and environmental phenomenology, and by well engineered hardware. These features not only afford assurance against gross accidents, they reduce to an acceptable level the possibility of escape of any radioactive products.

- The facility would be permanent and could be used frequently and continually. It would require minimum ground surface area. Permanent, well calibrated tools would record the results of nuclear tests.

- Because of the highly decoupled explosion and the reasonably small facility, the effect on the environment and the community should be minimal.

- The highly decoupled system would be an advantage if we were confronted with a test ban that imposed restrictions based on seismic levels (See Annex.2). In fact, the possibility of such a facility (plus other factors) raises the question as to whether any kind of a test ban can be technically significant.

- The initial cost for this facility would be significant, but total costs over a long period of time would be much less than we presently expend for underground testing. For example, we would need to drill no more holes; the security and labor force would be drastically reduced, and one would anticipate fewer labor disputes; the logistics and duplication of instrumentation would be minimized.

A complete description of a test facility based upon PACER principles and a comparison with current underground testing would require a considerable effort. It would be expected that the optimum configuration of a facility based upon PACER would include some elements remote from those currently associated with PACER.

CONCLUSIONS

- With present demands on the nuclear-weapons program diminishing, PACER device requirements could serve an important role in preserving and exercising the nuclear-weapons program.
- As a hedge against possible curtailment of the nuclear-weapons program, it may be desirable to accelerate the development of a PACER device.
- The PACER device may serve as an example of the kind of device that should be developed but which might not be developed if our nuclear-weapons program were stopped or severely curtailed.
- PACER principles could lead to a nuclear-device testing facility having many advantages over present underground testing methods. Such a facility warrants careful consideration in a period of tightening budgets, disinterest in nuclear weapons, ecological concern, and test bans.
- Finally, close association of the two programs could do much to advance the development of PACER. The financial and technical steps from the laboratory to significant (e.g., 1/100-th scale) PACER experiments in salt domes may be difficult, but the incentive afforded by prospects of the proposed test facility could encourage such a step.

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Los Alamos, New Mexico 87544

Annex 1

IN REPLY
REFER TO: DOS-1-74
(Revised)

November 28, 1973

CONSTRAINTS ON PACER THERMONUCLEAR EXPLOSIVES

Constraints on the design of the PACER thermonuclear device are as follows:

1. Security: Procedures for device manufacture, assembly, and handling must ensure that neither design information nor classified device components can be acquired by unauthorized personnel.

2. Safety: The device must be designed so that it is incapable, under any condition, of producing any nuclear yield prior to the intended time and place of explosion. The probability of destruction or of plutonium contamination through detonation of the device explosive must be remote. The device must also be designed to minimize the consequences of any accidental leakage of working fluid. PACER system design will, of course, make any such malfunction extremely improbable. Safety constraints place a premium on a device design that minimizes fission yield, residual plutonium, and induced radioactivity.

3. Natural Resources: The device should be designed to minimize demands on our natural resources. In particular:

- A minimum amount of SNM should be used.
- Deuterium should be emphasized as the thermonuclear fuel rather than tritium or lithium. Lavish use of tritium should be avoided, particularly if there is no practical way of recovery of generated tritium from a water working fluid. Lithium is impractical in the long run since, in terms of energy units, its supply is about as limited as that of fossil fuel.

4. Breeding: There will be a need for breeding plutonium and possibly tritium. A device designed to optimize plutonium breeding should use deuterium as a thermonuclear fuel to maximize neutron production. This simply emphasizes a previous requirement for the use of deuterium in preference to other fuels. Though there are some possible points of difference between PACER devices designed for breeding and those not so designed, these points are considered minor.

5. Cost: PACER devices must be produced at a cost that permits power production at a rate competitive with other means. The absence, within reason, of restrictions on weight, size, and environmental requirements will help in achieving this goal. However, to minimize cost under the constraints mentioned above will require an imaginative design program based on the latest technology and advanced production practices.

6. Yield: The device yield is expected to be between 10 and 100 kt. With today's technology, higher-yield devices are more cost effective and can be made to produce less radioactive products per kiloton than lower-yield devices. For this reason, early PACER studies have focused on a 100-kt thermonuclear energy source. On the other hand, a lower-yield device, say 10 kt, allows a tenfold reduction in cavity volume and thus reduces concern over cavity stability. It is therefore appropriate to investigate the entire yield range from 10 to 100 kilotons.

The foregoing constraints define the following approach for design of a PACER device:

1. Yields from 10 to 100 kt will be investigated.

2. The basic thermonuclear fuel will be deuterium. Use of tritium and lithium should be minimized.

3. Fission yield, SNM usage, and induced activity must be minimized. This goal should be possible since size and weight, within reason, are not restricted.

4. The device design and the procedures associated with its manufacture, assembly, and handling will emphasize security and safety as the main priorities. Under the cited constraints minimum cost is required.

Annex 2

R & D ASSOCIATES
P. O. Box 3580
Santa Monica, Calif. 90403

RDA-IR-4100-014

RELATIONSHIP OF THE PACER PROJECT TO A THRESHOLD TEST BAN

NOVEMBER 1973

By:
H. W. Hubbard
E. A. Martinelli

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The goal of the PACER project is to contain the energy released by thermonuclear explosives in a salt dome cavity and to use steam heated by these explosions to operate a conventional power plant. In the course of this project, it is proposed to conduct a series of scaled-down tests using 1 KT nuclear explosions. The cavity for these tests will be constructed at 1 to 1.5 km depth and will be about 80 to 100 meters in diameter. We want to suggest the continued use of this cavity for testing of nuclear weapons after the PACER experiments have been completed. Such a cavity could play an important role in the event of a threshold test ban, and it offers additional advantages as a test facility over underground testing in Nevada.

If a ban on nuclear testing is agreed upon, based on a seismic threshold, then it will be essential for the U.S. to have an adequately decoupled test facility which will allow the continuation of the most important tests. The bulk of U.S. underground testing is done at low yields -- 3/4 are below 10 KT -- and these are also the most important tests for weapon development. It is pertinent, therefore, to examine the effectiveness of the 100 meter diameter PACER cavity as a decoupling chamber for a 10 KT explosion.

Fortunately, there is direct experimental evidence which bears on the question of decoupling. In Project Sterling [1] a 380 ton nuclear device was detonated in a 34 meter diameter spherical cavity in a salt dome near Hattiesburg, Mississippi. The depth was 828 meters and the cavity contained only air at ambient conditions. The high pressure shock on the wall caused by the explosion was attenuated very rapidly in the salt and did not lead to an observable siesmic signal. The decoupling factor for the teleseismic signal was approximately 100. Since the strength of the shock at the wall scales as yield/volume for the same ambient pressure, the yield in the 100 meter cavity that would lead to the same shock on the wall is $0.38 \times (100/34)^3 \sim 10$ KT. The 100 meter size can therefore be expected to produce a teleseismic signal appropriate to a 100 ton explosion from an actual 10 KT test.

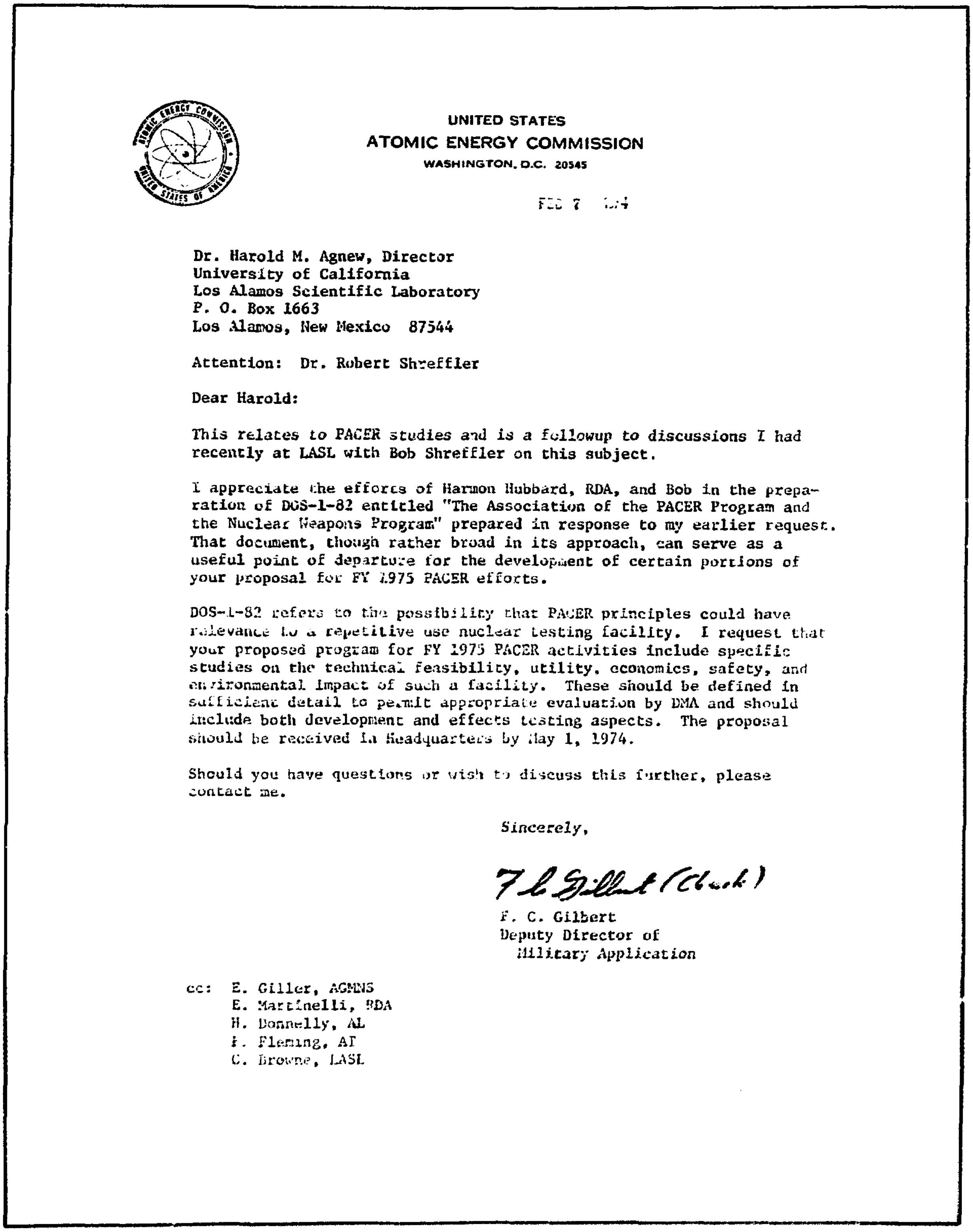
It is worth noting that, on re-entry, the cavity used for the Sterling experiment was intact, and could presumably have been used for another shot. Similarly, we have no reason to believe that a larger cavity would not be suitable for many explosions. Although the cavity radius is smaller than the fireball radius, and some salt will be melted after each explosion, rough estimates indicate that this is not a serious problem and that the cavity can be used repeatedly. The reusability of the facility will result in a considerable cost savings over that for the underground tests conducted in Nevada. In addition, the containment of the radioactive materials will be much surer than in the Nevada tests.

It is interesting to conjecture that the Russians may already have such a test facility. The AEC has announced two tests greater than 100 KT in the region of the Soviet Union where there are many salt domes. These explosions could have created cavities in the salt domes suitable for conducting decoupled tests in the 10 KT range, just as the U.S. 5 KT Salmon experiment created a stable cavity for the Sterling test.

REFERENCES

1. Sisemore, Clyde J., Leo A. Rogers, and William R. Perret, "Project Sterling: Subsurface Phenomenology Measurements Near a Decoupled Nuclear Event," J. Geophys. Res., Vol. 74, No. 27, December 15, 1969.

Ref. 28



UNITED STATES
ATOMIC ENERGY COMMISSION
WASHINGTON, D.C. 20545

FEB 7 1974

Dr. Harold M. Agnew, Director
University of California
Los Alamos Scientific Laboratory
P. O. Box 1663
Los Alamos, New Mexico 87544

Attention: Dr. Robert Shreffler

Dear Harold:

This relates to PACER studies and is a followup to discussions I had recently at LASL with Bob Shreffler on this subject.

I appreciate the efforts of Harmon Hubbard, RDA, and Bob in the preparation of DOS-1-82 entitled "The Association of the PACER Program and the Nuclear Weapons Program" prepared in response to my earlier request. That document, though rather broad in its approach, can serve as a useful point of departure for the development of certain portions of your proposal for FY 1975 PACER efforts.

DOS-1-82 refers to the possibility that PACER principles could have relevance to a repetitive use nuclear testing facility. I request that your proposed program for FY 1975 PACER activities include specific studies on the technical feasibility, utility, economics, safety, and environmental impact of such a facility. These should be defined in sufficient detail to permit appropriate evaluation by DMA and should include both development and effects testing aspects. The proposal should be received in Headquarters by May 1, 1974.

Should you have questions or wish to discuss this further, please contact me.

Sincerely,

F C Gilbert (Clark)

F. C. Gilbert
Deputy Director of
Military Application

cc: E. Giller, AGMNS
E. Martinelli, RDA
H. Donnelly, AL
J. Fleming, AI
C. Browne, LASL

Ref. 29

UNIVERSITY OF CALIFORNIA
LOS ALAMOS SCIENTIFIC LABORATORY
(CONTRACT W-7405-ENG-36)
P. O. Box 1663
Los Alamos, New Mexico 87544

IN REPLY
REFER TO: DOS-1-93

February 15, 1974

Dr. F. C. Gilbert
Division of Military Application
U. S. Atomic Energy Commission
Washington, D. C. 20545

Dear Chuck:

On your last trip to Los Alamos, we talked briefly about PACER. As I recollect, your comments on FY-1975 funding for PACER were that it would be limited and should be directed toward development of a nuclear test and effects site possibly along the lines suggested in the document that Harmon Hubbard and I wrote and sent to you: "The Association of the PACER Program and the Nuclear Weapons Program," DOS-1-82, dated November 29, 1973. You also discussed the subject with Ernest Martinelli of RDA. I later talked the matter over with Albert Latter and Harmon Hubbard of RDA and, later yet, with members of our Director's Office and J Division.

Let me first address the point that PACER principles provide the basic requirements for a nuclear-weapons testing and effects facility. Though I would hold with the opinions expressed in the cited document (with the possible exception of a few overenthusiastic adjectives), some of my more experienced colleagues argue that, from a technical point of view, much remains to be demonstrated in order to establish the technical feasibility of such an approach, not to mention proving it to be competitive with our current methods of underground testing. A particular point which is argued has to do with the restriction the method posed in the cited document would impose on radiochemical yield measuring techniques. Be that as it may, it would seem difficult to argue the point that any possible advantages of such a site should be brought sharply into focus when you have a political climate that is actively considering test bans of various descriptions. Quoting from the cited document:

> "The highly decoupled system would be an advantage if we were confronted with a test ban that imposed restrictions based on seismic levels (see Annex 2). In fact, the possibility of such a facility (plus other factors) raises the question as to whether any kind of a test ban can be technically significant."

AN EQUAL OPPORTUNITY EMPLOYER

Thus, no matter what the technical advantages, it seems to me that political necessities almost require that we explore the potential of such a test site.

Let me next quote the initial paragraph from Annex 2 of the cited document:

> "The goal of the PACER project is to contain the energy released by thermonuclear explosives in a salt dome cavity and to use steam heated by these explosions to operate a conventional power plant. In the course of this project, it is proposed to conduct a series of scaled-down tests using 1 kt nuclear explosions. The cavity for these tests will be constructed at 1 to 1.5 km depth and will be about 80 to 100 meters in diameter. We want to suggest the continued use of this cavity for testing of nuclear weapons after the PACER experiments have been completed.....".

With this background, let me now propose an approach that I think would best resolve the situation. We are working very hard to develop a program plan for PACER. We have divided it into three phases, the titles of which are self explanatory: Phase 1, Theoretical and Laboratory Studies; Phase 2, Scale Experiments; and Phase 3, Prototype Development. We are presently focusing our attention on Phase 1, Theoretical and Laboratory Studies and are preparing a document, DOS-1-81, that is nearing final-draft form. It consists of three parts; (1) program definition, which considers nine different projects with their associated tasks; (2) definition of laboratory experiments that support these tasks; and (3) a detailed budget. We have defined one of the nine projects as "Nuclear Test Site Definition." In order to review PACER and revise DOS-1-81 into final form, we are holding a two-day conference and meeting at LASL on February 21 and 22. At that time we will convene a special meeting between appropriate RDA and LASL people to consider in detail the "Nuclear Test Site Definition" project. The general purpose of the meeting will be to define the Phase 1 activities of this project and possibly incorporate it into Phase 2 of the PACER Program as proposed in the last quotation; i.e., the cavity and hardware of the scale experiment would be converted into a nuclear test site following the PACER Phase 2 experiments. We recognize at the outset that the PACER system may be more complicated than a system required solely for a nuclear test site. Indeed, the two systems may upon close scrutiny, be incompatible. We will have that answer only after Phase 1 has progressed toward completion.

Now permit me to leave the subject of nuclear-site definition and say a few words in support of the second element of PACER that can be closely associated with the Nuclear Weapons Program, namely device development. Annex 1 of the cited document defines the constraints and characteristics of the PACER nuclear device. Specifically, the device would be cheap to manufacture, burn deuterium, use minimum amounts of plutonium, oralloy, and tritium, and produce a minimum amount of fission products and induced activity. In short, it would present a challenge to our LASL weapons program to design and develop this device; the many devices required would more than maintain and stimulate our production facilities. I hope DMA will keep these points in mind when considering the PACER budget.

I intend to distribute DOS-1-81 by the end of February at which time the things I have outlined here will be more clear. The document will define a Phase 1 whose completion will require about $10 million. Our next step will be to prepare a one-hour briefing. We would like to come to Washington and meet with the same group that attended the last PACER session in Germantown. Our objective would be to obtain advice on how to acquire the funding we feel this project merits. Needless to say, I still consider PACER to be one of the most promising solutions to the world energy problem.

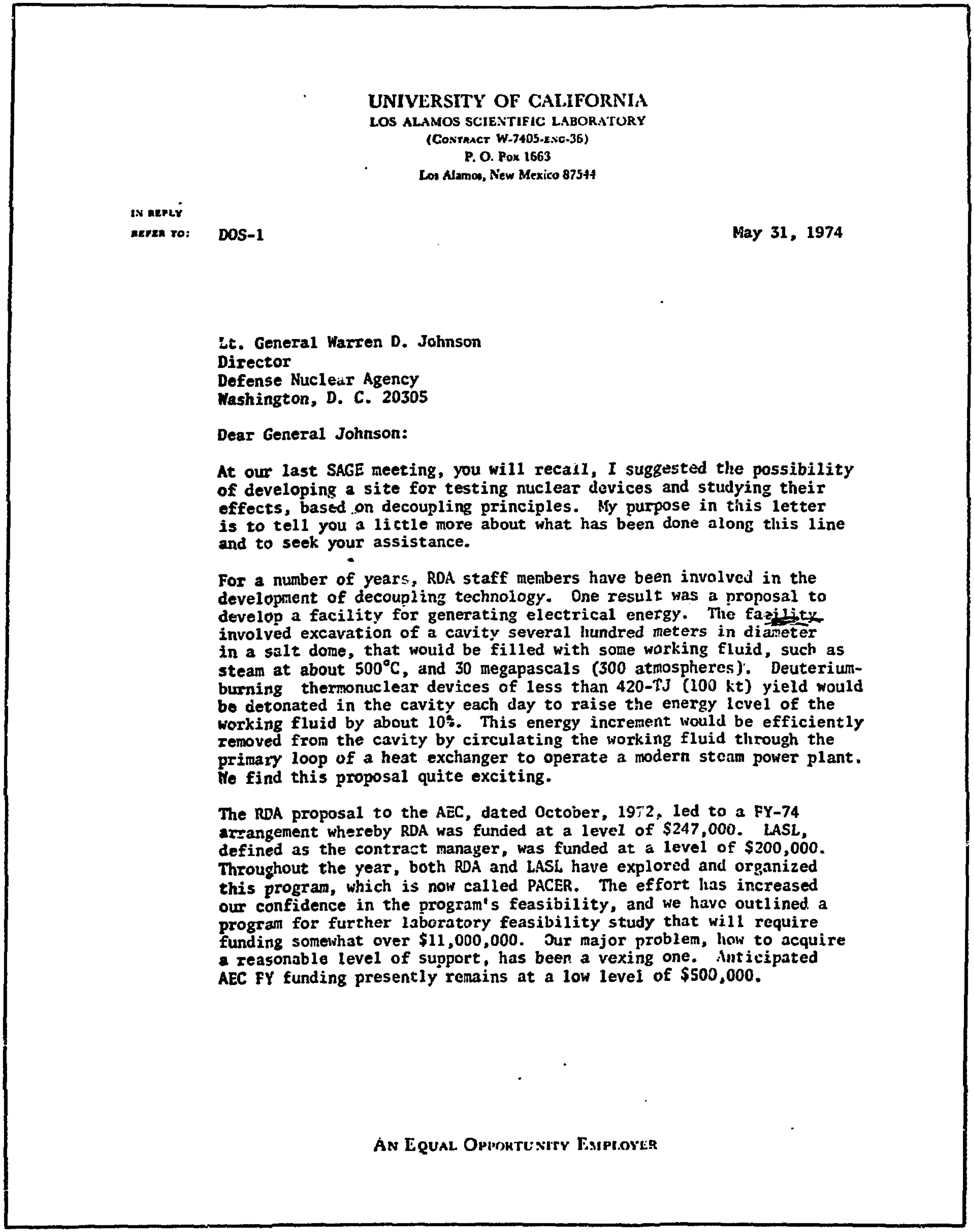
Sincerely,

R. G. Shreffler

RGS:rb
Distribution:
- A. Latter, RDA (2)
- H. C. Donnelly, ALO
- H. M. Agnew/R. E. Schreiber
- D. P. MacDougall
- R. F. Taschek
- C. I. Browne
- J. C. Hopkins
- R. Sharp
- ISD-5

P.S. Your letter of February 7 has arrived at a time when this letter was in final draft. It was much appreciated. Since both your and my letter seem to be in agreement, and since mine outlines our proposed plan in some detail, I'm sending it on to you.

Ref. 30



UNIVERSITY OF CALIFORNIA
LOS ALAMOS SCIENTIFIC LABORATORY
(CONTRACT W-7405-ENG-36)
P. O. Box 1663
Los Alamos, New Mexico 87544

IN REPLY
REFER TO: DOS-1 May 31, 1974

Lt. General Warren D. Johnson
Director
Defense Nuclear Agency
Washington, D. C. 20305

Dear General Johnson:

At our last SAGE meeting, you will recall, I suggested the possibility of developing a site for testing nuclear devices and studying their effects, based on decoupling principles. My purpose in this letter is to tell you a little more about what has been done along this line and to seek your assistance.

For a number of years, RDA staff members have been involved in the development of decoupling technology. One result was a proposal to develop a facility for generating electrical energy. The facility involved excavation of a cavity several hundred meters in diameter in a salt dome, that would be filled with some working fluid, such as steam at about 500°C, and 30 megapascals (300 atmospheres). Deuterium-burning thermonuclear devices of less than 420-TJ (100 kt) yield would be detonated in the cavity each day to raise the energy level of the working fluid by about 10%. This energy increment would be efficiently removed from the cavity by circulating the working fluid through the primary loop of a heat exchanger to operate a modern steam power plant. We find this proposal quite exciting.

The RDA proposal to the AEC, dated October, 1972, led to a FY-74 arrangement whereby RDA was funded at a level of $247,000. LASL, defined as the contract manager, was funded at a level of $200,000. Throughout the year, both RDA and LASL have explored and organized this program, which is now called PACER. The effort has increased our confidence in the program's feasibility, and we have outlined a program for further laboratory feasibility study that will require funding somewhat over $11,000,000. Our major problem, how to acquire a reasonable level of support, has been a vexing one. Anticipated AEC FY funding presently remains at a low level of $500,000.

In an effort to justify PACER on a valid weapon-support basis, DMA requested that we explore the possibilities of applying PACER principles to weapon activities. One result was a proposal to consider the feasibility of a nuclear test and effects site. This proposal cited a number of advantages of such a facility if it could be proven feasible:

- The safety of the facility would be assured by its existence in a stable homogeneous medium, by a thoroughly understood cavity and environmental phenomenology, and by well engineered hardware. These features might not only afford assurance against gross accidents, they might reduce to an acceptable level the possibility of escape of any radioactive products.
- The facility could be permanent and used frequently. It would require minimum ground surface area. Permanent, well calibrated tools could record the results of nuclear tests.
- Because of the highly decoupled explosion and the reasonably small facility, the effect on the environment and the community should be minimal.
- The highly decoupled system could be an advantage if we were confronted with a test ban that imposed restrictions based on seismic levels. In fact, the possibility of such a facility (plus other factors) raises the question as to whether any kind of a test ban can be technically significant.
- The initial cost for this facility would be significant, but total costs over a long period of time could be much less than we presently expend for underground testing. For example, if feasible for high enough yields, we would need to drill no more holes; the security and labor force could be drastically reduced, and one would anticipate fewer labor disputes; the logistics and duplication of instrumentation could be minimized.

To gain necessary confidence in such a proposal and determine its limitations, I feel we must carry out the project rather completely. The estimated cost for the detailed laboratory study is estimated to be $1.1 million. We have high confidence in the concept, but we still need to qualify nearly every aspect of the project. Let me cite an example. We will need to study the relative advantages of forming cavities in hard rock (such as found at the Nevada Test Site) and in salt domes. We presently feel that hard-rock cavity mining would be unpredictable and costly, with the cost per unit volume of mined rock increasing with cavity volume. In salt domes, cavity mining is relatively predictable and inexpensive, with cost per unit volume of mined salt decreasing with cavity volume. As a result, development of small hard-rock cavities supporting decoupled explosions below 42 TJ (10 kt) would probably be feasible at NTS. Testing with device yields up to 1 Mt may be feasible in salt-dome cavities. Development of hard-rock and, particularly, salt-dome cavities has been studied extensively, and the results have led us to these tentative conclusions; but a great deal of information still needs to be studied to permit sound conclusions.

Although this proposal is being made at a time when its feasibility might bear strongly on the formulation of a test ban, I feel its cited advantages could make it the most sensible way for us to continue nuclear and effects testing into the future. In any case, we won't know until we investigate the subject. Other reasons for pressing the study are its nominal cost and the fact that both RDA and LASL are well equipped and anxious to undertake the study.

I hope you might find this program of interest in a supporting role to the DNA mission. At any rate, any advice you or your staff might offer would be much appreciated.

LASL and RDA staff members will be glad to discuss the matter with you at any time.

Sincerely,

R. G. Shreffler

RGS:rb
cc: J. Rosengren, DNA
A. Latter/H. Hubbard, RDA
E. Graves/C. Gilbert, DNA
R. LeLevier, Chairman SAGE, RDA
H. Agnew/D. MacDougall/R. Taschek, LASL
E. Hammel, LASL
C. Browne, LASL
ISD-5
File

Ref. 31

DEFENSE NUCLEAR AGENCY
WASHINGTON, D.C. 20305

DDST

27 JUN 1974

Dr. Robert Shreffler
Los Alamos Scientific Laboratory
P. O. Box 1663
Los Alamos, New Mexico 87544

Dear Bob,

The PACER concept mentioned in your letter of 31 May 1974 is a fascinating concept for the generation of electric power. It also looks like a very difficult environment in which to do repetitive nuclear effects tests. Your proposal raises a large number of questions, considering the difficulties as well as the advantages of this type of facility.

The documents you and Dr. Hubbard sent to Dr. Oakley helped greatly by showing the many facets of the concept that have already been investigated.

The cavity concept appears to present the possibility of a broader range of test yields under a tight seismic threshold that might eventually come to exist for a TTBT. Independent of that, such a cavity might provide opportunities for new forms of nuclear effects tests under the LTBT.

Our preliminary conclusions are that the project has considerably more to offer the AEC than it does DNA -- that the AEC should have more interest in investigating the possibilities. Therefore, we would propose that the AEC lead the way in funding such investigations. We and our advisors will be considering possible effects applications of such facilities, and we will discuss these with you in the near future.

DDST
Dr. Robert Shreffler

Thank you very much for bringing this extremely interesting idea to my attention. We will give it serious study.

Sincerely,

Don

WARREN D. JOHNSON
Lieutenant General, USAF
Director

PS: I suspect the next steps in the nuclear testing business will be a CTBT (after the TTBT now being discussed.) The question is when & whether the period before it is signed would permit amortization of investment in something like Pacer. The tone of this letter is a bit more negative than I like. Certainly we should discuss this further.

Ref. 32

APPENDIX D

STATEMENT OF WORK

CONTRACT NO. AT(29-2)-3324

A. GENERAL

At the level of effort described in paragraph c. of ARTICLE 1 - STATEMENT OF WORK of the contract, the Contractor shall use its best efforts to achieve the objective set forth in B. below.

B. OBJECTIVE

The objective for this year's (FY 75) work is to initiate the identification and assessment of the critical problems affecting the feasibility of safely and economically using an underground cavity as a nuclear test facility.*

To accomplish this objective, the Contractor shall conduct a program consisting of, but not limited to the following tasks, as said tasks may be varied by project direction given the Contractor pursuant to paragraph f. of ARTICLE 1 - STATEMENT OF WORK of the contract.

Task 1 - Cavities for Nuclear Test Facility

Investigate the feasibility of mining cavities for a nuclear test facility. In performing this investigation, specific attention should be given to the sites available at NTS. This study should include a comprehensive cost versus cavity size comparison and recommendation as to engineering feasibility of optimum cavity size and shape.

---

*A complete project to determine the theoretical feasibility of a nuclear test and effects facility is outlined in DOS-1-81, "PACER PROGRAM - Phase 1, Theoretical and Laboratory Studies," previously furnished to the Contractor.

Task 2 - Cavity Phenomenology

Consistent with findings in Task 1, a detailed investigation should be generated to determine:

1. maximum yield of test device to permit reuse of the cavity,
2. effects on cavity wall due to nuclear explosion,
3. teleseismic signal decoupling of appropriate range of yields, and
4. medium within cavity to reduce nuclear explosion effects on the walls to a minimum, but compatible with test diagnostics. Said diagnostic techniques shall be supplied by the LASL Project Director.

Task 3 - Engineering

Recommend safe and feasible methods for injecting the nuclear test device into the cavity, positioning and recovery of diagnostic equipment.

Task 4 - PACER PROGRAM Description

Prepare a written description of the overall PACER PROGRAM. Such description shall be prepared in a manner which will permit the preparation of presentations which will lead to an evaluation of the PACER PROGRAM and its future funding.

Task 5 - Reports

In addition to other reports required by the Contracting Officer pursuant to paragraph 5. of ARTICLE VIII - ACCOUNTS, RECORDS AND INSPECTION of Appendix B, the Contractor shall prepare and furnish the following technical reports to the Contracting Officer (one copy) and the LASL Project Director (three copies) in such form and detail as required by the LASL Project Director:

a. Quarterly Progress Reports and

b. a final report which summarizes the accomplishments during this year, together with a recommendation and supporting justification for continuation of the program.

Ref. 33

LOS ALAMOS SCIENTIFIC LABORATORY
UNIVERSITY OF CALIFORNIA
LOS ALAMOS, NEW MEXICO 87544

OFFICE MEMORANDUM

TO : R. F. Taschek

DATE: February 13, 1974

FROM : R. G. Shreffler

SUBJECT : PACER BUDGET

SYMBOL : DOS-1

A 189a for the PACER program is attached. I strongly recommend that it be adopted as the basis for PACER's inclusion in the Laboratory budget for the coming fiscal years. I would also propose that the 189a be sent to Fleming, Graves and Giller with a strong Laboratory endorsement. If you disagree I'd like to talk the matter over with you immediately. Probably we should get Harold and Duncan into the act.

R. G. Shreffler

RGS:rb
Enc: 189a for PACER
cc: D. P. MacDougall, w/enc.
H. M. Agnew, w/o enc.

Ref. 34

UNIVERSITY OF CALIFORNIA
LOS ALAMOS SCIENTIFIC LABORATORY
(CONTRACT W-7405-ENG-36)
P. O. Box 1663
Los Alamos, New Mexico 87544

IN REPLY
REFER TO: DOS-1-94

February 26, 1974

Mr. Michael Daly
Senator Joseph M. Montoya's Staff
United States Congress
Washington, D.C. 20515

Dear Mike:

Harold Agnew requested that I send you information on PACER, a program to generate electric power by tapping the energy from thermonuclear explosions. We have been working quite hard on this program at Los Alamos and with scientists at Research and Development Associates (RDA), Santa Monica, California. As the project leader I can hardly behave objectively; however my opinion is that PACER has promise to supply a significant fraction of the world's energy requirements.

The attachment is an introduction to a planning document defining the first phase of this program. This introduction gives a brief outline of PACER. I will send you a copy of the complete document in a few weeks.

During the next month we plan to develop a briefing based upon the original proposal by RDA and the work we have done in the past fiscal year. We would welcome the opportunity to present this briefing to you.

Regards,

Bob Shreffler

R. G. Shreffler

RGS:rb
cc: H. M. Agnew

Ref. 35

UNITED STATES
ATOMIC ENERGY COMMISSION
WASHINGTON, D.C. 20545

APR 18 1974

Dr. Robert G. Shreffler
University of California
Los Alamos Scientific Laboratory
P. O. Box 1663
Los Alamos, New Mexico 87544

Dear Bob:

Thank you very much for your letter of March 21, 1974, inviting me to the next meeting of the LASL Tactical Nuclear Panel. I have received the notice of April 4 setting the date on May 14-15. Unfortunately, other commitments will prevent my attending, but DMA will be represented.

It was good to see you last week at the time of the discussion of PACER. I hope this program can proceed at a meaningful level with support from both the weapons program and the applied technology program. We are working on the funding problem here in Headquarters. We look forward to hearing from you further as you address the issues we discussed in last week's meeting.

Sincerely,

Ernie

Ernest Graves
Major General, USA
Assistant General Manager
for Military Application

DOS-1-107

Working Paper
April 25, 1974

PACER

PROPOSED OBJECTIVES AND BUDGET FOR FY 75

This document sets the goals and defines the level of effort for the PACER program in FY 75. It assumes the content and follows the format laid out in DOS-1-81. The total budget for FY 75 is $500,000. It is split equally between LASL and RDA.

PROJECT 1. THERMONUCLEAR DEVICE

Task 1.1 Device Design

- o Design of 10 and 100 kt devices completed.

Task 1.2

- o Preliminary cost figure completed.

Task 1.3 Device

- o Preliminary outline of safety and security Requirements

LASL	Ceiling Points
DOS-1	0.5
TD-2	0.1
RDA	0.05

PROJECT 2. CAVITY PHENOMENOLOGY

Task 2.1

- o Decide working fluid (H_2O, CO_2, or ?) (Addressed under Project 9.)

Task 2.2

- o Complete radflo calculations defining behavior of working fluids. Energy deposited in wall and seismic effects determined.

Task 2.3 Circulation of working fluid

- Apply CIRCO to calculate circulation with various engineering configurations. (Addressed under Project 3, Engineering.)
- Determine history of fireball.

Task 2.4 Cavity Integrity - Creep Effects

- Complete code development
- Calculate selected problems

Efforts in this area during FY 75 will be applied to Project 8.

PROJECT 3 ENGINEERING

Task 3.1 Trade Studies

- Attention will be concentrated on the development of engineering approaches and concepts.
- CIRCO (T-3 Circulation Code) will be employed.

Task 3.2 Primary Loop

- Conceptual design of primary loop and Experiment 3 will be developed.

Task 3.3 Materials

- Impact of Experiment 1, Materials Selection, will be reviewed.

Task 3.4 Containment

- Containment problems and solutions will be addressed.

Task 3.5 Device Injection

- Device injection concepts developed.

LASL	Ceiling Points
ENG	0.7
RDA	0.4

PROJECT 4 ECONOMICS

See Project 9

PROJECT 5 SAFETY AND ENVIRONMENTAL CONSIDERATIONS

See Project 9

PROJECT 6 FUEL RECOVERY AND PROCESSING

- Importance of working fluid cleanup. The relative advantages, in this regard, of various working fluids will be considered, e.g., it may be possible to recover the tritium from a CO_2 working fluid.
- The advantages and disadvantages of breeding ^{239}Pu
- The advantages and disadvantages of breeding ^{233}U

	Ceiling Points
RDA	1.0

PROJECT 7 - GEOLOGY, SITE DEFINITION AND SELECTION AND CAVITY CONSTRUCTION

- Program will continue as outlined in DOS-1-81.
- Attention will be concentrated upon cavity construction.
- Relative merits of salt vs hard rock will be given attention.

Effort in this area during FY 75 will be applied to Project 8.

PROJECT 8 NUCLEAR TEST AND EFFECTS FACILITY

- A summary document will be written at the end of FY 75 covering all aspects of this program as outlined in DOS-1-81. This document will attempt to be as comprehensive and complete as possible; however, it should be understood that this project as outlined in DOS-1-81 is budgeted at $1,148,000; it also assumes a much higher FY 75 PACER budget in support of other projects.

- Principal attention will be focussed upon the feasibility of the development of a site at NTS.

- Further funding of the project through ARPA and DNA will be pursued.

LASL	Ceiling Points
DOS-1	0.20
J-6	1.00
J-7	0.10
J-10	0.10
T-3	0.05
T-4	0.10
WX-2	0.50
WX-3	0.25
Total	2.30
RDA	1.25*

*RDA funding will be explored with ARPA and DNA. Current ARPA budget on closely associated project at RDA is 0.6 C.P. For FY 75 it is hoped that the average effort from outside the AEC will be at least 1.3 C.P.

PROJECT 9 SYSTEM ANALYSIS, COORDINATION AND PLANNING

The following goals are set for this project:

1. Develop optimization procedures for PACER.
2. Update DOS-1-81.
3. Write preliminary proposal on Phase 2.
4. Give particular attention to Project 5, Safety and Environmental Considerations.

LASL	Ceiling Points
DOS-1	0.4
T-3	0.05
RDA	0.5

PACER PHASE 1 EXPERIMENTAL PROGRAM

Expt. No.	Experiment Name
1	Materials Selection
2	Halite Creep Rupture Experiments
3	Primary Loop Mockup
4	Shaft Sealing
5	Device Injection
6	Dynamic Loading of Access Piping
7	Steam-Cavity Wall Interaction
8	Laboratory Cavity Experiment
9	Anhydrite Creep Experiment
10	Radiation Deposition in Salt

During the course of the year the definitions and descriptions of the above experimental programs as outlined in DOS-1-81 will be critically reviewed.

LASL	Ceiling Points
WX-2	0.5
RDA	0.1

FY 75 FUNDING SUMMARY

LASL	Ceiling Points		Funding $K
DOS-1	1.1		61
ENG-6	0.7		36
J-6	1.0		46
J-7	0.1		5
J-10	0.1		7
T-3	0.1		7
T-4	0.1		7
TD-2	0.1		7
WX-2	1.0		50
WX-3	0.25		24
Total C.P.	4.55	Subtotal	250
RDA	3.3		250
		TOTAL	$ 500

Ref. 37

UNIVERSITY OF CALIFORNIA
LOS ALAMOS SCIENTIFIC LABORATORY
(CONTRACT W-7405-ENG-36)
P. O. Box 1663
Los Alamos, New Mexico 87544

IN REPLY
REFER TO: DIR

April 26, 1974

Major General Ernest Graves
Assistant General Manager for
Military Application
U. S. Atomic Energy Commission
Washington, D. C. 20545

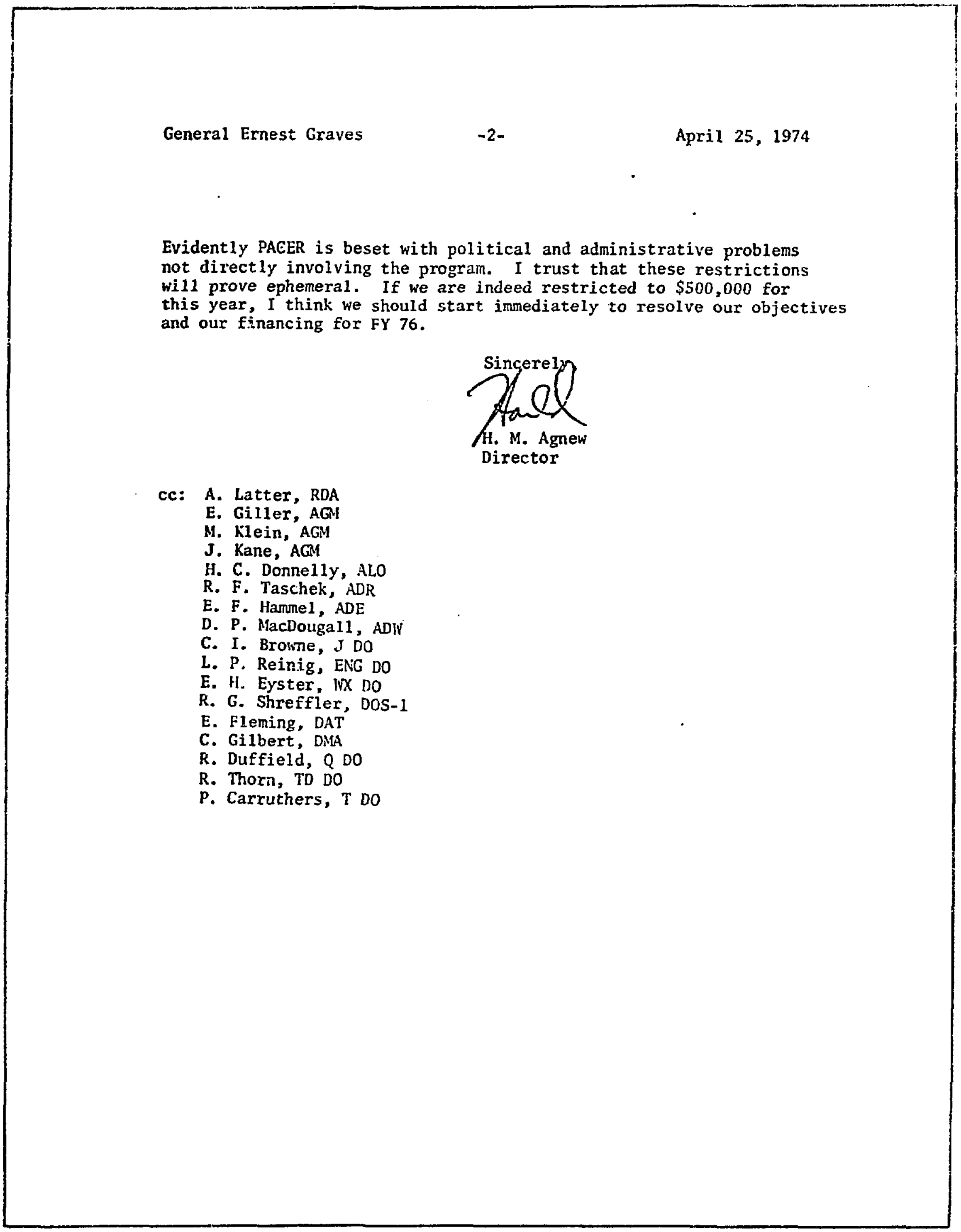
Dear General Graves:

Attached are two documents. The first, DOS-1-107, outlines the PACER objectives and the budget for FY 75 based on assumed funding of $500,000. The second, DOS-1-81, outlines the initial phase of the PACER Program and is the reference for DOS-1-107. Both documents should be considered working papers, and we would appreciate any suggestions AEC Headquarters might have for improving them.

Both documents (under Project 8) address the feasibility study for a nuclear-test-and-effects facility. In this regard, I can add little to the statement in DOS-1-107. The project description and its total associated budget ($1,148,000) as outlined in DOS-1-81 require a considerable amount of additional fleshing out and refinement, but I doubt that we will deviate much from the basic approach.

I am concerned about the low level of proposed funding since PACER seems to have great technical potential for an ultimate and early solution to the energy problem. There is little doubt that addressing the feasibility of a nuclear-test-and-effects facility will sustain and improve our understanding of PACER, but, to some degree, the facility represents a diversion and saps funding from the energy goal. If we are serious about the facility, we should invest the funds necessary to determine its feasibility. If we think PACER warrants serious technical attention as an energy source--and I think it does--we should fund it accordingly.

So that there will be no misunderstanding I cannot accommodate the required 500K from our planned FY 75 funds even with our anticipated share of the $15M add-on test money if it survives the budget cycle.



Evidently PACER is beset with political and administrative problems not directly involving the program. I trust that these restrictions will prove ephemeral. If we are indeed restricted to $500,000 for this year, I think we should start immediately to resolve our objectives and our financing for FY 76.

Sincerely,

H. M. Agnew
Director

cc: A. Latter, RDA
E. Giller, AGM
M. Klein, AGM
J. Kane, AGM
H. C. Donnelly, ALO
R. F. Taschek, ADR
E. F. Hammel, ADE
D. P. MacDougall, ADW
C. I. Browne, J DO
L. P. Reinig, ENG DO
E. H. Eyster, WX DO
R. G. Shreffler, DOS-1
E. Fleming, DAT
C. Gilbert, DMA
R. Duffield, Q DO
R. Thorn, TD DO
P. Carruthers, T DO

Ref. 38

LOS ALAMOS SCIENTIFIC LABORATORY
UNIVERSITY OF CALIFORNIA
LOS ALAMOS, NEW MEXICO 87544

OFFICE MEMORANDUM

TO : Distribution

DATE: May 8, 1974

FROM : R. G. Shreffler

SUBJECT : TRANSMITTAL OF DOS-1-111, PACER - PROPOSED OBJECTIVES AND BUDGET FOR FY 75

SYMBOL : DOS-1

The attached budget is consistent with Form 189a transmitted on April 19, 1974.

for R. G. Shreffler

Distribution:
Gen. Ernest Graves, AGM, USAEC
Gen. E. B. Giller, AGM, USAEC
M. Klein, AGM, USAEC
J. Kane, AGM, USAEC
E. Fleming, DAT, USAEC
F. C. Gilbert, DMA, USAEC
H. C. Donnelly, ALO
D. K. Nowlin, ALO (2)
V. C. Vespe, ALO
A. Latter, RDA (2)
H. Agnew/D. MacDougall, DIR
R. F. Taschek, ADR
E. F. Hammel, ADE
R. D. Baker, CMB DO
C. I. Browne, J DO
P. A. Carruthers, T DO
G. A. Cowan, CNC DO
W. E. Deal, M DO
R. B. Duffield, Q DO
E. H. Eyster, WX DO
L. P. Reinig, ENG DO
R. N. Thorn, TD DO
R. R. Sharp, J-6
F. P. Schilling, ENG-6
T. J. Merson, ENG-6
T. D. Butler, T-3
J. F. Barnes, T-4
L. C. Smith, WX-2
A. W. Nutt, WX-2
J. G. Marinuzzi, ADE
G. M. Smith, FMO
J. Aragon, WX-3
C. A. Anderson, WX-3
R. E. Roush, DOS-1
DOS-1 File
ISD-5

DOS-1-111
May 7, 1974
Working Paper

PACER
PROPOSED OBJECTIVES AND BUDGET FOR FY 75

This document sets the goals and defines the level of effort for the PACER program in FY 75. It assumes the content and follows the format laid out in DOS-1-81. The total assumed budget for FY 75 is $3.5M: $2.0M LASL, $1.1M RDA and $0.4M Engineering Support

This document is intended as a substitute or follow-on to DOS-1-107 which addresses a $500,000 FY 75 budget. Anytime within the FY LASL and RDA could increase their level of effort to meet the spending rate defined in the following pages, assuming that there has been no other increased manpower demands within the Laboratory from ongoing or new programs.

Project 1. Thermonuclear Device

Task 1.1 Device Design

- Design of 10 and 100 kt devices completed.
- Engineering design of external hardware and preliminary development tests initiated.
- Devide output calculated

Task 1.2 Device Cost

- Preliminary cost figures completed.

Task 1.3 Device Safety and Security

- Preliminary outline of safety and security requirements

	Ceiling Points
LASL	
DOS-1	0.25
TD-1	0.25
TD-2	0.25
WX-1	0.5
WX-3	0.25
RDA	0.1

Project 2 Cavity Phenomenology

Task 2.1 Working Fluid

- o Decide working fluid (H_2O, CO_2, or?)

Task 2.2 Nuclear Explosion Investigation ($t < 1$ sec)

- o Complete radflo calculations defining behavior of working fluids.
- o Energy deposited in wall and seismic effects determined.

Task 2.3 Circulation of working fluid

- o Apply CIRCO to calculate circulation with various engineering configurations (Addressed under Project #3).
- o Determine history of fireball.

Task 2.4 Cavity Integrity - Creep Effects

- o Complete code development
- o Calculate selected problems

LASL	Ceiling Points
J-10	0.5
T-3	0.5
T-4	0.5
WX-2	0.5
WX-3	0.5
RDA	1.0

Project 3 Engineering

Task 3.1 Trade Studies

- o Attention will be concentrated on the development of engineering approaches and concepts
- o CIRCO (T-3 Circulation Code) will be employed

Task 3.2

- o Conceptual design of primary loop completed. Experiment #3 will be designed, and procurement initiated; see Experiment #3.

Task 3.3 Materials

- Impact of Experiment 1, Materials Selection, will be reviewed.

Task 3.4 Containment

- Candidate solutions to the shaft sealing problem will be designed and scale tests will be planned. (See Experiment #4, Shaft Sealing.)

Task 3.5 Device Injection

- Device injection concepts developed. Model tests will be planned (See Experiment #5, Device Injection.)

LASL	Ceiling Points
ENG-6	1.5
J-6	1.0
J-7	0.5
RDA	1.5

Project 4 Economics

0 A continuous updating of the overall estimated costs of the PACER plant will be done. Comparisons will be made with other proposed solutions to the energy problem.

	Ceiling Points
LASL	
DOS-1	0.1
RDA	0.2

Project 5 Safety and Environmental Considerations

Task 5.1 Safety Implications

- A continuous review of all the safety aspects of the PACER system will be carried out.

Task 5.2 Seismic Effects

- Develop and apply codes to calculate the seismic effect of the impulse from the nuclear explosion on all components of the system, as well as ground effects at the surface.

Task 5.3 Government Safety Regulation

- Survey governmental safety and environmental regulations. Interpret and propose courses of action to comply with regulations.

Task 5.4 PACER promotion

Prepare and update briefings on PACER. Develop visual aids.

		Ceiling Points
LASL		
	DOS-1	0.25
	ENG-6	0.25
	J-9	0.50
RDA		0.5

Project 6 Fuel Recovery and Processing

- Determine importance of working fluid cleanup. The relative advantages, in this regard of various working fluids will be considered, e.g., it may be possible to recover tritium from a CO_2 working fluid.
- The advantages and disadvantages of breeding ^{239}Pu.
- The advantages and disadvantages of breeding ^{233}U.
- Conceptual designs for equipment for the above tasks developed.

		Ceiling Points
LASL		
	DOS-1	0.1
	CMB-11	0.25
	TD-3	0.25
	WX-2	0.25
RDA		1.5

Project 7 Geology, Site Definition and Selection and Cavity Construction

- Complete survey of U.S. salt domes
- Establish criteria for salt dome site selection
- Make preliminary survey of types and locations of hard rock sites, and determine preliminary site selection criteria
- Determine cavity formation cost in salt domes and hard rock

		Ceiling Points
LASL		
	J-6	0.5
	J-7	0.5
RDA		2.0

Project 8 Feasibility Study for Nuclear Test and Effects Facility

It is intended that Project 8 be completed within FY 75. As a consequence, the project as defined in DOS-1-81 is appended in its entirety.

	Ceiling Points
LASL	
DOS-1	0.6
CNC-11	0.5
H-1	0.5
J-DO	0.5
J-1	0.1
J-6	1.5
J-7	1.2
J-8	1.1
J-9	2.0
J-10	0.6
J-12	0.6
J-14	0.8
J-15	0.9
J-16	1.0
T-3	0.2
T-4	0.2
WX-2	0.2
WX-3	0.3
RDA	4.7

Project 9 System Analysis, Coordination and Planning

- Develop optimization procedures for PACER
- Update DOS-1-81
- Write Preliminary proposal for Phase 2
- Coordinate and monitor all aspects of PACER

	Ceiling Points
LASL	
DOS-1	0.5
RDA	1.5

PACER Phase 1 Experimental Program

Experiment #1. Materials Selection

- Conduct materials compatibility tests as outlined in RDA-JTR-4100-1, Preliminary Material Evaluation Pre-Test Report for PACER Program.

	Ceiling Points
LASL	
WX-2	1.0
CMB-6	0.5
RDA	0.2

Experiment #2 - Halite Creep Rupture

- Determine creep rupture criteria

	Ceiling Points
LASL	
WX-3	0.75
RDA	0.2

Experiment #3 Primary Loop Mockup

- o Develop conceptual design, engineer and initiate procurement; see Task 3.2

	Ceiling Points
LASL	
ENG-6	1.0
RDA	1.0

Experiment #4 Shaft Sealing

- o Conduct scale laboratory experiments on shaft sealing concepts.

	Ceiling Points
LASL	
ENG-6	0.25
J-7	0.25
RDA	0.2

Experiment #5. Device Injection

- o Plan experiment in conjunction with Tasks 3.5 and 8.3.

	Ceiling Points
LASL	
J-7	0.2
RDA	0.1

Experiment #6. Dynamic Loading

- o Experimental concept resolved

	Ceiling Points
LASL	
M-6	0.1
RDA	0.1

Experiment #7 Steam-Cavity Interface

- o Conduct laboratory experiments on possible cavity wall defect growth

	Ceiling Points
LASL	
WX-2	0.2
RDA	0.3

Experiment #8 Laboratory Cavity Experiment

- o Detailed definition and investigation of experiment. Investigate possible use of PUFF facility

	Ceiling Points
LASL	
DOS-1	0.2
RDA	0.5

Experiment #9 Anhydrite Creep

- o Creep tests will be conducted.

	Ceiling Points
LASL	
WX-3	0.25
RDA	0.1

Experiment #10

- o Measure radiation absorbtion in salt under working conditions.

	Ceiling Points
LASL	
WX-2	0.5
RDA	0.1

FY 75 Funding Summary ($3.5M)

LASL	Ceiling Points		Funding $K
DOS-1	2.0		125.0
CMB-5	0.5		25.0
CMB-11	0.25		12.5
CNC-11	0.5		30.0
ENG-6	3.0		234.0
H-1	0.5		29.0
J-DO	0.5		27.0
J-1	0.1		6.0
J-6	3.0		169.0
J-7	2.65		146.0
J-8	1.1		62.5
J-9	2.5		162.0
J-10	1.1		77.0
J-12	0.6		40.0
J-14	0.8		46.0
J-15	0.9		61.0
J-16	1.0		57.0
M-6	0.1		5.0
T-3	0.7		42.0
T-4	0.7		42.0
TD-1	0.25		15.0
TD-2	0.25		15.0
TD-3	0.25		15.0
WX-1	0.50		75.0
WX-2	2.65		159.0
WX-3	2.05		123.0
Total Ceiling Points	28.45	Subtotal	1800.0
		Capital Equipment (LASL)	200.0
RDA	15.6		1100.0
Engineering Support			400.0
		TOTAL	$ 3500.0

PROJECT 8 : Feasibility Study for Nuclear Test and Effects Facility

PROJECT LEADER:

DESCRIPTION :

It has been proposed (reference 1) that the principles and techniques developed in the PACER program could be applied to the development of a nuclear test and effects site that, if proven feasible, might have certain advantages:

- The safety of the facility would be assured by its existence in a stable homogeneous medium, by a thoroughly understood cavity and environmental phenomenology, and by well engineered hardware. These features might not only afford assurance against gross accidents, they might reduce to an acceptable level the possibility of escape of any radioactive products.
- The facility could be permanent and used frequently. It would require minimum ground surface area. Permanent, well calibrated tools could record the results of nuclear tests.
- Because of the highly decoupled explosion and the reasonably small facility, the effect on the environment and the community should be minimal.
- The highly decoupled system could be an advantage if we were confronted with a test ban that imposed restrictions based on seismic levels. In fact, the possibility of such a facility (plus other factors) raises the question as to whether any kind of a test ban can be technically significant.
- The initial cost for this facility would be significant, but total costs over a long period of time could be much less than we presently expend for underground testing. For example, if feasible for high enough yields, we would need to drill no more holes; the security and labor force could be drastically reduced, and one would anticipate fewer labor disputes; the logistics and duplication of instrumentation could be minimized.

It should be noted that nuclear tests have been fired in cavities in the past. Sterling is an example of a low yield (380 tons) test in a salt dome cavity. Cannikin, although not effectively decoupled, is an example of a much higher yield experiment done in a mined cavity and accompanied by complex diagnostics.

The definition of a test site would follow closely the outline of the PACER program as stipulated in the first seven Projects of this document. The amount of effort required would depend upon the effort already incorpoated into PACER.

The specific tasks defining this project are the following:

Task 8.1	Project Planning and Coordination
Task 8.2	Cavity Phenomenology
Task 8.3	Engineering
Task 8.4	Nuclear Test and Effects Diagnostics
Task 8.5	Safety and Environmental Considerations
Task 8.6	Site Definition, Selection, and Cavity Engineering
Task 8.7	Cost

RESOURCES:

The resources are spelled out with each of the tasks. It should be noted that the capabilities of both RDA and LASL are admirably suited for such a project. At LASL a large share of responsibility will reside in J Division.

STATUS:

Reference 2 proposes that Reference 1 serve as a point of departure for the development of a nuclear testing facility. It requests that "the FY 75 PACER activities include specific studies on the technical feasibility, utility, economics, safety, and environmental impact of such a facility. These should be defined in sufficient detail to permit appropriate evaluation by DMA and should include both development and effects testing aspects. The proposal should be received in Headquarters by May 1, 1974."

Reference 3 documents intended LASL/RDA opinion and proposed activity on this project.

All group leaders have been contacted and estimated manpower inputs received.

REFERENCES:

1. The Association of the PACER Program and tne Nuclear Weapons Program, DOS-1-82, November 29, 1973, Harmon Hubbard and R. G. Shreffler.

2. F. C. Gilbert to H. M. Agnew, Letter dated February 7, 1974.

3. R. G Shreffler to F. C. Gilbert, Letter dated February 15, 1974.

4. For associated experiments see the corresponding tasks of PACER.

5. J6-74-65, Group Estimates of Manpower Requirements for One Year Feasibility Study of a Reusable Nuclear Test and Effects Facility as Proposed in PACER Project 8.

TASK 8.1 : Project Planning and Coordination

PROJECT LEADER:

DESCRIPTION :

The purpose of this task is to plan, coordinate, and report on the progress of this project. A primary function will be to establish criteria for the various tasks. Such parameters as test yield limitations, test frequency, and seismic decoupling factor must be established. Operating procedures and site specifications will be defined. Safety and security will be given primary consideration.

RESOURCES:

DOS-1	Coordination with rest of PACER
J-DO	Planning and coordination of Project 8
J-6	Collection and assimilation of data from J Division groups.
RDA	

STATUS:

All Group Leaders at LASL have been contacted and estimated manpower inputs received.

REFERENCES:

1. J6-74-65, Group Estimates of Manpower Requirements for One Year Feasibility Study of a Reusable Nuclear Test and Effects Facility as Proposed in PACER Project 8.

TASK 8.2 : Cavity Phenomenology

PROJECT LEADER:

DESCRIPTION :

The following subjects will be addressed.

1. A selection of the cavity size and depth consistent with choices made in Task 8.1.
2. An investigation of the effects of the nuclear explosion (t < 1 sec).
3. Determination of teleseismic signal decoupling over a range of parameters.
4. An investigation of the feasibility of cavity reusability.
5. Investigation of cavity stability.

To a large degree this task will employ the techniques and results generated by Project 2, Cavity Phenomenology.

RESOURCES:

DOS-1	Coordination
J-10, J-15, T-4	Investigation of nuclear explosion (t<1 sec).
J-9	Determination of teleseismic signal
T-3	Investigation of nuclear explosion (t>1 sec).
J-6	Investigation of cermets and grouts to withstand effects at cavity boundary.
J-7	Investigation of materials and designs to withstand effects at cavity boundary.
J-8	Electronics support to J-9 investigations.
RDA	

STATUS:

REFERENCES:

See documents listed under Tasks of Project 2.

TASK 8.3 : Engineering

PROJECT LEADER:

DESCRIPTION:

This task will consider all the engineering except for the mining of the cavity. This will include the surface installation, the pipes and cabling connecting the surface with the cavity, the cassette containing the test device and instrumentation, the equipment for lowering the cassette, and any device used for cooling the cavity. At the present time it is difficult to carry the description of the engineering much further. Tasks 8.1 and 8.2 must proceed to better resolve a description of the site.

RESOURCES:

J-6	Civil and coordination
J-7	Mechanical
J-8	Electrical
J-9	Design input
J-12	Design input
J-14	Design input
J-16	Design input
CNC-11	Design input
RDA	

STATUS:

REFERENCES:

1. See Project 3, this report.

TASK 8.4 : Nuclear Test and Effects Diagnostics

PROJECT LEADER:

DESCRIPTION:

The purpose of this task is to select the best diagnostic techniques. It is probable that most instrumentation will be included in a cassett which also contains the nuclear device. At the outset it is not obvious how radiochemistry can be used. Reliance must be shifted to first sampling and dependence on short half-lived isotopes. This difficulty may be further compensated by the validity associated with blast and flux (γ and η) measurements in the homogeneous cavity media.

Equal priority will be given to the execution of effects tests. This would include the configuration of typical experiments along with instrumentation. An attempt should be made to design methods for exposure followed by recovery.

RESOURCES:

CNC-11	Radiochemical Analysis
J-8	Electronics Support
J-9	Predictions
J-10	Predictions
J-12	PINEX, etc.
J-14	Yield measurements
J-15	Effects predictions
RDA	

STATUS:

Preliminary talks have been held

REFERENCES:

TASK 8.5 : Safety and Environmental Considerations

PROJECT LEADER:

DESCRIPTION:

Safety is the watchword of this project. In many regards the project has advantages from the safety point of view:

- The installation is installed in a relatively homogeneous medium, the behavior of which will be carefully studied.
- The explosions will be highly decoupled giving minimum insult to the cavity walls and the hardware.
- The hardware is permanently installed; it is carefully and conservatively engineered; it is sealed to reduce to an acceptable level any leakage to the surface.

The specific definition of the safety problem will depend upon a description of the system as developed under Tasks 8.1, 8.2, and 8.3.

The following four sub-tasks must be considered:

- Examine each aspect of the concept and design for the safety implications.
- Resolve to a sensible degree the expected seismic effects of the nuclear explosion upon all the mechanical components of the system, and the effects at the surface of the ground.
- Investigate the legal implications of the project from the safety point of view.
- Resolve how and when the project should be presented to the public.

MILESTONES:

RESOURCES:

J-1
J-6
J-7
J-8
J-9
J-10
J-15
H-1
CNC-11
RDA

STATUS:

Same

REFERENCES:

TASK 8.6 : Site Definition, Selection, and Cavity Engineering

PROJECT LEADER: RDA, Rawson/LASL, Sharp

DESCRIPTION:

In practically all respects this task is identical with PACER Project 7.

MILESTONES:

RESOURCES:

J-6	Field surveys
J-9	Geophysical studies
RDA	

STATUS:

REFERENCES:

TASK 8.7 : Cost

PROJECT LEADER:

DESCRIPTION:

The cost of the project will be estimated. This will include the capital investment, the operating cost, and the cost incurred in the execution of a nuclear test. Much of this information will be available from the other projects of the PACER program.

MILESTONES:

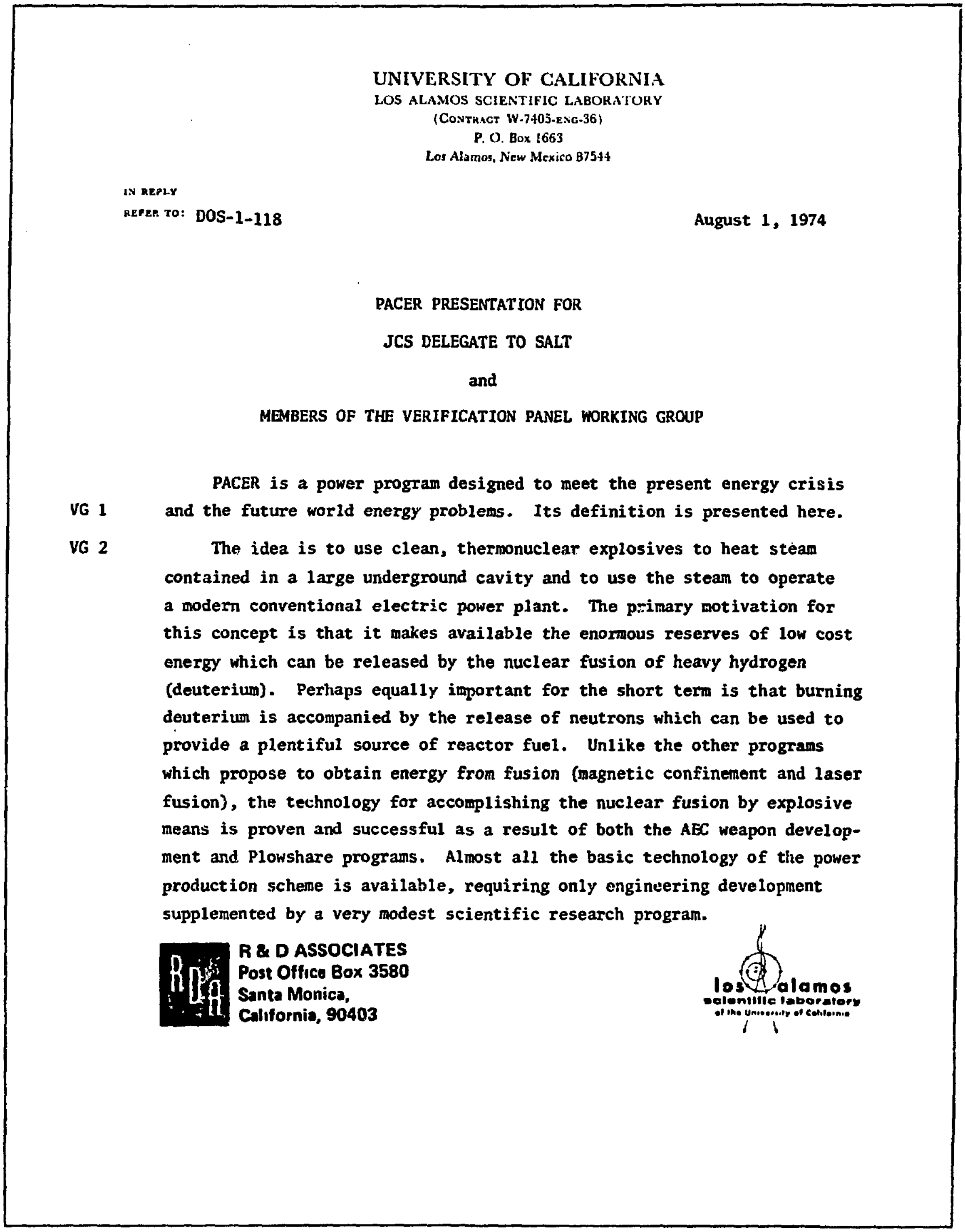
RESOURCES:

DOS-1
J-6
J-7
J-8
J-9
J-12
J-14
J-15
J-16
H-1
RDA

STATUS:

REFERENCES:

Ref. 39



UNIVERSITY OF CALIFORNIA
LOS ALAMOS SCIENTIFIC LABORATORY
(CONTRACT W-7405-ENG-36)
P. O. Box 1663
Los Alamos, New Mexico 87544

IN REPLY
REFER TO: DOS-1-118

August 1, 1974

PACER PRESENTATION FOR
JCS DELEGATE TO SALT
and
MEMBERS OF THE VERIFICATION PANEL WORKING GROUP

PACER is a power program designed to meet the present energy crisis
VG 1 and the future world energy problems. Its definition is presented here.

VG 2 The idea is to use clean, thermonuclear explosives to heat steam contained in a large underground cavity and to use the steam to operate a modern conventional electric power plant. The primary motivation for this concept is that it makes available the enormous reserves of low cost energy which can be released by the nuclear fusion of heavy hydrogen (deuterium). Perhaps equally important for the short term is that burning deuterium is accompanied by the release of neutrons which can be used to provide a plentiful source of reactor fuel. Unlike the other programs which propose to obtain energy from fusion (magnetic confinement and laser fusion), the technology for accomplishing the nuclear fusion by explosive means is proven and successful as a result of both the AEC weapon development and Plowshare programs. Almost all the basic technology of the power production scheme is available, requiring only engineering development supplemented by a very modest scientific research program.

R & D ASSOCIATES
Post Office Box 3580
Santa Monica,
California, 90403

los alamos
scientific laboratory
of the University of California

The behavior of a specific version of the PACER system which shows how one might contain a fifty kiloton fusion explosion within a 300 meter diameter cavity in a salt dome is shown here. This process is repeated about twice each day to supply energy for a 2000 megawatt power plant.

VG 3 An artist's conception of the surface installation is shown here. Note the device injection system, the pipes which transmit the working fluid to and from the surface, the heat exchangers, the debris scrubbers, and the containment vessel. I intend to say little about the turbines, the cooling tower, and the transmission system, except to recognize that they are items which are common to almost all power plants, and are procurable from the shelf.

VG 4 From this viewgraph I can describe some important features of the system:

- Of prime importance is the design of a system which can be demonstrated, a priori, to be safe. We accomplish a great deal in this regard by employing a large cavity which "decouples" the explosion from the environment. The geometry shown here demagnifies the effects of the explosion by a factor of 100, minimizing surface effects and permitting the hardware to be reused many thousands of times.
- The small quantity of soluble fission fragments, the tritium, and the induced activities all from the device explosion are diluted to almost insignificant levels in the large mass of working fluid--to the order of a part per million after a few years, assuming no cleanup of the working fluid.
- Attention is focused upon the hardware again with safety over a 20-year life cycle in mind. Alloys must be developed and tested; the cavity must be isolated from the surface with proper seals, heat exchangers, and other devices.

- Salt domes present a near optimum site for the cavity. The deposits are relatively massive, pure, and the salt of the cavity well is plastic and self sealing at PACER working conditions.
- Although superheated steam is a preferred working fuid, CO_2 and air are also being considered.

VG 5 With this background, I would like to now shift to the most important element of the system, the fusion device. An advanced design is shown here. Such a system is designed to minimize the consumption of tritium and plutonium. It produces minimum fission products. It "burns" the ultimate fuel, deuterium. It could be designed to produce any yield within reason. Of course, systems which burn lithium and larger quantities of SNM's must be considered as well. A major task is to demonstrate that such devices can be built cheaply and handled safely and securely. A goal is to make a device such as the one shown here at a cost about one order of magnitude cheaper than current quoted AEC costs for Plowshare devices--a task which we consider attainable in light of the large numbers of devices required, which permits mass production techniques, the relaxed restrictions on size and weight, and an inexhaustable supply of cheap deuterium fuel plus minimum use of SNM's.

An essential output of a fusion device has been mentioned in my introductory remarks, namely its neutrons. With each kiloton of fusion yield are generated about 2 moles of neutrons. By adding blankets of uranium or thorium around the device one can breed relatively pure ^{239}Pu or ^{233}U, respectively, and in very large quantities--of the order of a quarter of a kilogram per kiloton of fusion yield. ^{233}U has the advantages that it is more easily handled and it can be diluted with ^{238}U converting it into a fuel material not useable in weapons. The bred materials can be burned in cheap, efficient reactors, at least to meet the present crisis; expensive breeder reactors would not be required. For each kiloton of fusion energy generated in the PACER cavity one breeds fissile material for about four kilotons of energy from the fission reactors.

From the foregoing description it should be obvious that the PACER Concept includes many options determined by such features as the fusion device design, the choice of containment medium, the choice of working fluid, the employment of breeding, the specific engineering solutions, etc. Upon more careful investigation, obviously some of these options will fall by the wayside; however there is no question in our minds that a number of options can be developed into power devices which produce power safely, at a lower cost than it can be produced by any other means, in as short a time, and indefinitely into the future.

VG 6 The principal advantages of the PACER concept are encapsulated here. I'll leave the vugraph on the screen while I summarize our activities to date.

Historically, this concept is not new. It was put forward--rather
unsuccessfully--by Brobeck in 1957. In October of 1972 R&D Associates,
based upon their experience with nuclear decoupling experiments, proposed
the system much as I have described it. In FY 74 the AEC funded the
program at the half million dollar level with RDA as the prime contractor
and LASL as the contract manager. Throughout FY 74 the two laboratories
developed the concept further, perfected codes for more precise calculations,
VG 7 and organized the first phase of the program into the projects shown here.
VG 8 These were supplemented with a set of laboratory experiments noted here.
This initial laboratory phase will cost in the order of ten million dollars.
One objective of the initial phase would be to define additional phases
around field experiments which would lead ultimately to a prototype system.

VG 9 This fiscal year our efforts have been concentrated upon the application of PACER principles to the development of a test site for nuclear devices and nuclear effects. At the same time our planning continues on the PACER Energy Concept, in the hope of increased funding in support of our ten year goal.

List of Vugraphs

VG No.	
1	PACER Definition
2	2000 MW Power Plant (CN74 1243)
3	PACER Surface Installation
4	(VG #2 Repeat)
5	Preliminary Pacer Device Physics Design
6	PACER Advantages
7	PACER Program, Phase 1
8	PACER Experiments, Phase 1
9	Project 8, Nuclear Test and Effects Site, Possible Advantages)

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PACER DEFINITION

PACER IS A PROGRAM WHICH USES KNOWN TECHNOLOGY TO CONVERT THE ENERGY FROM REPEATED HIGH YIELD FUSION EXPLOSIONS TO ELECTRIC POWER.

THE GOAL OF THE PROGRAM IS TO CONSTRUCT A PROTOTYPE POWER PLANT WITHIN TEN YEARS.

Vu-graphs 2, 3, and 4 omitted in this report.

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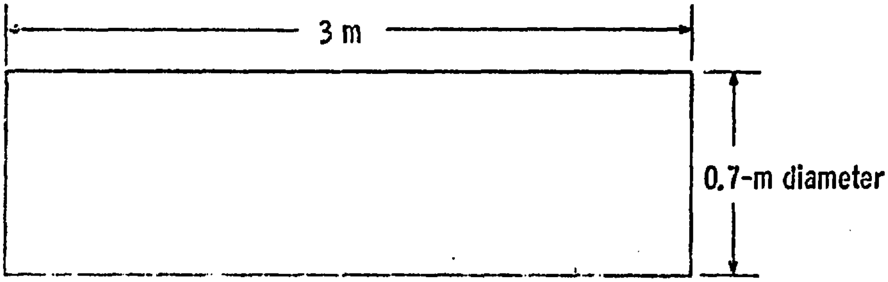
PACER EXPLOSIVE



YIELD: 100 kt maximum
WEIGHT: 1500 kg

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PACER ADVANTAGES

- MEETS WORLD ENERGY REQUIREMENT
- LOW COST, INEXHAUSTABLE, CLEAN FUEL
- TEN YEAR TIME SCALE, KNOWN TECHNOLOGY
- MINIMUM ECOLOGICAL IMPACT
- BREEDING OF FISSILE MATERIAL MAGNIFIES POWER POTENTIAL FIVEFOLD
- NATIONAL POWER INDEPENDENCE
- REPLACES OTHER APPROACHES TO POWER PROBLEM
- HIGH DEGREE OF CONTROL AND SAFETY

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PACER PROGRAM

PHASE 1

PROJECT 1	THERMONUCLEAR DEVICE
PROJECT 2	CAVITY PHENOMENOLOGY
PROJECT 3	ENGINEERING
PROJECT 4	ECONOMICS
PROJECT 5	SAFETY AND ENVIRONMENTAL CONSIDERATIONS
PROJECT 6	FUEL RECOVERY AND PROCESSING
PROJECT 7	GEOLOGY, SITE DEFINITION AND SELECTION AND CAVITY CONSTRUCTION
PROJECT 8	NUCLEAR TEST AND EFFECTS SITE DEFINITION
PROJECT 9	SYSTEM ANALYSIS, COORDINATION AND PLANNING

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PACER
EXPERIMENTS

EXPERIMENT NO.	EXPERIMENT NAME
1	MATERIAL SELECTION
2	HALITE CREEP RUPTURE EXPERIMENTS
3	PRIMARY LOOP MOCKUP
4	SHAFT SEALING
5	DEVICE INJECTION
6	DYNAMIC LOADING OF ACCESS PIPING
7	STEAM-CAVITY WALL INTERACTION
8	LABORATORY CAVITY EXPERIMENT
9	ANHYDRITE CREEP EXPERIMENT
10	RADIATION DEPOSITION IN SALT

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PROJECT 8

NUCLEAR TEST AND EFFECTS SITE

POSSIBLE ADVANTAGES

- THE SAFETY OF THE FACILITY WOULD BE ASSURED BY ITS EXISTENCE IN A STABLE HOMOGENEOUS MEDIUM, BY A THOROUGHLY UNDERSTOOD CAVITY AND ENVIRONMENTAL PHENOMENOLOGY, AND BY WELL ENGINEERED HARDWARE. THESE FEATURES NOT ONLY AFFORD ASSURANCE AGAINST GROSS ACCIDENTS, THEY REDUCE TO AN ACCEPTABLE LEVEL THE POSSIBILITY OF ESCAPE OF ANY RADIOACTIVE PRODUCTS.

- THE FACILITY WOULD BE PERMANENT AND COULD BE USED FREQUENTLY AND CONTINUALLY. IT WOULD REQUIRE MINIMUM GROUND SURFACE AREA. PERMANENT, WELL CALIBRATED TOOLS WOULD RECORD THE RESULTS OF NUCLEAR TESTS.

- BECAUSE OF THE HIGHLY DECOUPLED EXPLOSION AND THE REASONABLY SMALL FACILITY, THE EFFECT ON THE ENVIRONMENT AND THE COMMUNITY SHOULD BE MINIMAL.

- THE HIGHLY DECOUPLED SYSTEM WOULD BE AN ADVANTAGE IF WE WERE CONFRONTED WITH A TEST BAN THAT IMPOSED RESTRICTIONS BASED ON SEISMIC LEVELS. IN FACT, THE POSSIBILITY OF SUCH A FACILITY (PLUS OTHER FACTORS) RAISES THE QUESTION AS TO WHETHER ANY KIND OF A TEST BAN CAN BE TECHNICALLY SIGNIFICANT.

- THE INITIAL COST FOR THIS FACILITY WOULD BE SIGNIFICANT, BUT TOTAL COSTS OVER A LONG PERIOD OF TIME WOULD BE MUCH LESS THAN WE PRESENTLY EXPEND FOR UNDERGROUND TESTING. FOR EXAMPLE, WE WOULD NEED TO DRILL NO MORE HOLES; THE SECURITY AND LABOR FORCE WOULD BE DRASTICALLY REDUCED, AND ONE WOULD ANTICIPATE FEWER LABOR DISPUTES; THE LOGISTICS AND DUPLICATION OF INSTRUMENTATION WOULD BE MINIMIZED.

ECOLOGICAL & SAFETY IMPACT

ADVANTAGES

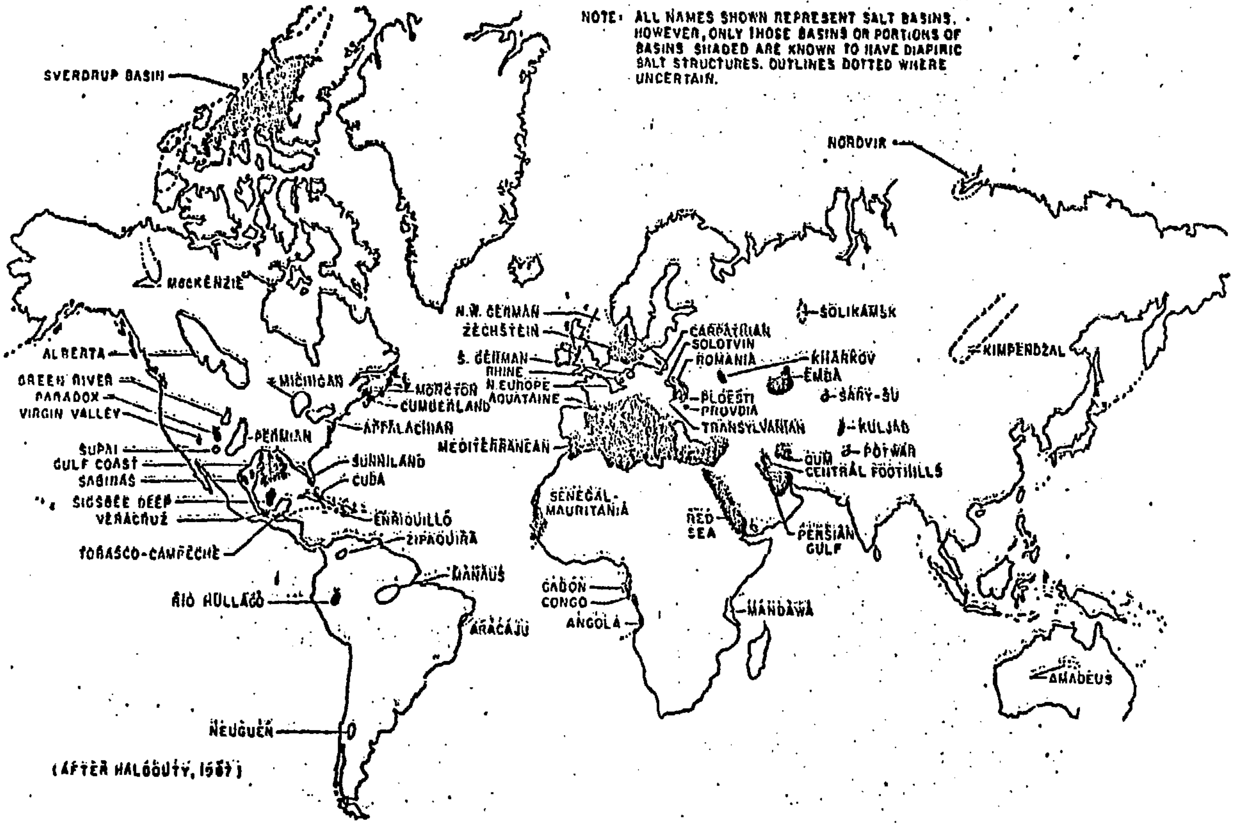
- LOW LEVEL RADIOLOGICAL HAZARD
- NO ATMOSPHERIC POLLUTION
- LOW IMPACT ON REAL ESTATE
- LOW MANPOWER REQUIREMENTS
- LOW HAZARD POTENTIAL
- EXCURSION FREE
- HIGH CONTROL OF FISSILE MATERIAL
- MINIMUM FISSILE MATERIAL HANDLING PROBLEM

DISADVANTAGES

- THERMAL POLLUTION
- PREDISPOSITION OF PUBLIC AGAINST USE OF NUCLEAR DEVICES

LASL ISD-7

74 7308



NOTE: ALL NAMES SHOWN REPRESENT SALT BASINS. HOWEVER, ONLY THOSE BASINS OR PORTIONS OF BASINS SHADED ARE KNOWN TO HAVE DIAPIRIC SALT STRUCTURES. OUTLINES DOTTED WHERE UNCERTAIN.

(AFTER HALBOUTY, 1967)

MAJOR SALT BASINS OF THE WORLD
FIGURE 31.

Ref. 40

LOS ALAMOS SCIENTIFIC LABORATORY
UNIVERSITY OF CALIFORNIA
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OFFICE MEMORANDUM

TO : Distribution DATE: August 15, 1973

FROM : R. G. Shreffler

SUBJECT : ELECTRIC POWER GENERATION BY THERMONUCLEAR EXPLOSIONS CONTAINED IN SALT DOMES. JULY 1973 PROGRESS REPORT

SYMBOL : DOS-1-58

The progress made on this program during the month of July 1973 is summarized in the two attachments.

R. G. Shreffler

RGS:rb

Attachments:

1. Monthly Technical Progress Report, Harmon W. Hubbard, 6 August 1973.
2. Monthly Technical Progress Report (July), R. G. Shreffler/R. Roush, 15 August 1973.

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F. Schilling, LASL ENG 6
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R. N. Thorn, LASL TD-DO
ISD-5
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IN REPLY REFER TO: DOS-1-59

August 15, 1973

REPORT OF WORK DONE AT LASL DURING THE MONTH OF JULY, 1973 ON ELECTRIC POWER GENERATION

The following is a brief summary of the activities carried on by LASL.

1) A general information meeting was held on July 6 to review the approach to the program. The results of this meeting are summarized in Reference 1.

2) A meeting was held at RDA on July 24. It was attended by:

RDA	LASL
H. Hubbard	R. Shreffler
D. Griggs, UCLA	F. Schilling
B. Lindgren	A. Nutt
F. Gillmore	R. Roush
N. Kfoury	
H. Brode	
A. Fields	

The subjects of major interest were reviewed.

3) Reasonable progress is being made on those subjects reviewed at the July 6 meeting. It is as yet too early to present specific results.

4) A major portion of the time at LASL has been devoted to organization of the Program. The current commitment of funds is summarized in the following table.

		$K
DOS-1	(Program Management)	38.2
ENG	(Engineering Design)	16.7
T	(Hydrodynamic Calculations)	25.8
WX	(Physical Chemistry)	19.3

R. G. Shreffler

R. E. Roush

Reference 1: Electric Power Generation by Thermonuclear Explosions Contained in Salt Domes. Meeting July 6, 1973 at LASL.

AN EQUAL OPPORTUNITY EMPLOYER

R & D ASSOCIATES
P.O. Box 3580
Santa Monica, Calif. 90403

RDA-TR-4100-001

MONTHLY TECHNICAL PROGRESS REPORT

Harmon W. Hubbard

6 August 1973

Sponsored by:

U.S. Atomic Energy Commission
Washington, D. C. 20545

Contract AT(29-2)-3324

REPORT OF WORK DONE AT RDA DURING THE MONTH OF JULY 1973
ON CONTRACT AT(29-2)3324

Shock Formation

In order to determine the size of the fireball at breakaway, i.e., when the shock forms in the dense gas in the cavity, the early time fireball behavior was studied. The model which fits Brode's calculations [1] for sea level explosions is as follows.

1. Initially almost all the energy is in the radiation field. The radiation "diffuses" outward but with a sharp front. Diffusion is in the sense that the radius to the front is related to the time by $R^2 = Dt$.

2. As the sphere expands and cools, energy goes from radiation into particle motion, and when a point is reached that the energy is mainly in the matter, the radiation front is no longer "diffusing" but is governed by an equation of the form $R^{3(3+n)+2} \sim t$, where n gives the power of the temperature dependence for the Rosseland mean free path. Even for $n = 0$ this implies a very slight increase with time so at this point the shock forms and runs out in front.

3. This model implies that the shock breakaway radius scales as

$$\frac{R_1}{R_2} = \left(\frac{W_1}{W_2}\right)^{1/3} \left(\frac{\rho_2}{\rho_1}\right)^{4/9} \left(\frac{Z_2 + 1}{Z_1 + 1} \cdot \frac{A_1}{A_2}\right)^{4/9}$$

where 1 and 2 are the two cases being compared, ρ is ambient density and Z and A are charge and mass number of the gas and W is the energy yield.

H. L. Brode, "Review of Nuclear Weapons Effects," The RAND Corporation, Santa Monica, California, March 1968.

In every gas at the density implied by 500°C and 440 bars, the breakaway radius is smaller than for an explosion in sea level air. Since the sea level breakaway radius is ≈22 meters for 100 KT, the explosion can always be considered a point source as far as the first shock on the wall is concerned. The results for H_2O are therefore as reported in the RDA proposal 72-26 and can be scaled for other gases.

Thermal Pulse

Some fraction of the infrared, visible and ultraviolet radiation emitted by the fireball during the "first pulse," (i.e., while the shock is running out), will reach the wall before the shock. Whether a sufficient amount will reach the wall to vaporize any significant amount of salt depends on the opacities of the gas and the optical properties of polycrystalline salt. These parameters are being calculated and/or assembled.

The radiation from the "second pulse" is normally very large; ∿1/3 of the yield for a sea level explosion. It is hoped that the slightly heated air (500°C plus shock heating) will be sufficiently absorbing to prevent the radiation from reaching the wall. If not, the effect of debris will have to be considered, or even addition of absorbing poisons.

To do the complete radiant emission problem, either a transport code must be used, or some modification of a diffusion code to include "grey body" emission from ∿ one mean free path; the code should be ready when the material properties are ready.

Engineering Materials

The general advantages and disadvantages of some of the common materials was reviewed by A. Tetelman (UCLA). The use of hydrogen as a working fluid was strongly discouraged since high yield strength steels are very susceptible to embrittlement and cracking by H_2. The effect of small concentrations of H_2 which would be present in H_2O is not known yet. Low carbon steels (which must be cathodically protected) or copper alloy pipe would not be attacked by hydrogen. Further materials data is being gathered.

Fracture of Salt

Discussions with A. Tetelman (UCLA) reconfirmed our opinion that the only way the salt can propagate a crack is for it to go into tension. Since our parameters will be chosen specifically to avoid this possibility, the problem areas will be restricted to metal-salt interfaces. A shear could conceivably develop between the pipe and the salt, and propagate an opening. A way in which this might happen physically has not been visualized, but the possibility will be analyzed.

Working Fluid

Hydrogen will not be further considered at RDA as a working fluid, because it offers no advantage and causes engineering problems (see above). The original thought was that the shock might form at a sufficiently large radius to reduce the pulse on the wall but this is not the case as explained in the section above on Shock Formation.

Inert gases (A, N_2) are good from the corrosion standpoint, but LASL data indicate they are too expensive to consider. We are therefore left with air, water, air from which the O_2 has been burned out, or CO_2 as remaining candidates. The first phenomenology calculations will be done with air and next H_2O.

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OFFICE MEMORANDUM

TO : Distribution

DATE: September 10, 1973

FROM : R. G. Shreffler

SUBJECT : ELECTRIC POWER GENERATION BY THERMONUCLEAR EXPLOSIVES CONTAINED IN SALT DOMES. AUGUST 1973 PROGRESS REPORT

SYMBOL : DOS-1-62

The progress made on this program during the month of August, 1973, is summarized in the two attachments.

R. G. Shreffler

RGS:rb

Attachments:

1. Monthly Progress Report, H. W. Hubbard, RDA-MR-4100-001, September 1973
2. Monthly Progress Report, R. G. Shreffler/R. Reush, DOS-1-63, September 1973

Distribution:

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D. K. Nowlin, ALO (2)
V. C. Vespe, ALO
A. Latter, RDA (2)
H. M. Agnew/D. P. MacDougall, LASL DIR
Frank Harlow, LASL T-3
J. Russell, LASL TD-7
D. Venable, LASL M DO
F. Schilling, LASL, ENG 6
R. H. Campbell, LASL J DO
R. Alire, LASL WX-2
R. N. Thorn, LASL TD DO
ISD-5
File

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P. O. Box 1663
Los Alamos, New Mexico 87544

IN REPLY
REFER TO: DOS-1-63

September 10, 1973

REPORT OF WORK DONE AT LASL DURING THE MONTH OF AUGUST, 1973, ON ELECTRIC POWER GENERATION

The following is a brief summary of the activities carried on by LASL.

- Preliminary calculations have been made by J-10 on the early phases ($t < 1$ sec) of the thermonuclear device explosion (100 kt) in the 400 meter diameter salt cavity with air as a working fluid (ambient conditions: $T = 600°C$, $P = 440$ bars). During this time the problem is one dimensional. The following results are significant.

  1. Essentially no radiation reaches the wall. Evidently the presence of NO_2, an almost unique infrared absorber, is responsible for this fortunate conclusion. (See RDA portion of report.)

  2. The fireball expands to a radius of 50 meters, with a high uniform temperature of about 7 volts.

  3. The reflected hydrodynamic shock in the wall was about as expected (∿ 900 bars).

- Preliminary calculations*have been made to study the rise of the 50 meter fireball in the cavity. It used as its input the results of the calculation just described at a time of 0.1 sec. The results depicted the fireball rising to the top of the cavity in about 12 sec. During this rise it has become distorted with the internal temperature falling to about 1200°C, a drastic drop from 7 volts. (Some of this drop may be artificial, a consequence of the calculational method.)

- T-3 is preparing to do this two dimensional problem with the precision which will produce an accurate description of the fireball history as it splashes against the top of the cavity. These calculations will continue in time to give an exposition of the circulation of the working fluid within the cavity as it is influenced by the explosion and fluid as it is being removed and rejected from the primary loop.

- T- is perfecting better opacity inputs for air and water in the domain of interest.

---

*By J-10; a LAMS is being prepared on this calculation.

- Attention has been given to thermonuclear explosives design. The attached memorandum (DOS-1-61) covers all areas of LASL interest in the development of explosives for use in the Energy Program.

- WX-3 is modeling the salt dome to study plastic flow of the cavity wall over its lifetime using the PLAST-T Code.

- WX-2 is addressing the selection of the working fluid. A document is being prepared in conjunction with RDA. It is believed that definitive experiments relative to the H_2O/NaCl system can be performed within the current budget.

- A Management System is being generated in close coordination with RDA as a matter of priority. The familiar format (Program, Project, Task) is being employed. The project headings are:

  Project 1: Thermonuclear Explosive Design
  Project 2: Cavity Phenomenology
  Project 3: Investigation of Engineering Feasibility
  Project 4: Economics
  Project 5: Safety and Environmental Considerations
  Project 6: Breeding and Recovery of Special Nuclear Materials.

- A meeting was held at RDA on August 17, 1973. The program was reviewed. The following people were in attendance:

RDA	LASL
Arlen Field	Robert G. Shreffler
Forrest Gilmore	A. W. Nutt
Linn Gore	
Harmon Hobbard	
Bob Lindgren	
Ernest Martinelli	
George Safnov	
Richard Turco	

RDA-MR-4100-001

MONTHLY PROGRESS REPORT

REPORT OF WORK DONE AT RDA DURING THE MONTH OF AUGUST 1973 ON CONTRACT AT(29-2)3324

SEPTEMBER 1973

By:
H. W. HUBBARD

Sponsored by:

U. S. ATOMIC ENERGY COMMISSION
Washington, D. C. 20545

REPORT OF WORK DONE AT RDA DURING THE MONTH OF AUGUST 1973 ON CONTRACT AT(29-2)3324

PRIMARY LOOP ENGINEERING CONCEPTS

In order to alleviate the problem of designing 6400 psi heat exchange equipment, the idea of throttling the steam down to a pressure of ∿2500 psi has been proposed. The throttling is accomplished by taking frictional losses in a pipe of sufficiently small diameter leading to the heat exchanger. The "losses" are, however, not permanent since the heat diffuses only slowly into the surrounding salt. The net effect is a change in the system temperature distribution as well as some drop in temperature (to ∿810°F) of the steam to the exchanger. The great advantages of this concept are that (1) a flow appropriate to 2000 Mw electric can be accommodated in a 2 to 3 ft diameter pipe, and (2) more or less standard power generating equipment can be used. The pumping power required to return condensed liquid water to the cavity is ∿100 Mw.

Preliminary investigation shows alternative schemes to be much less efficient and/or more costly.

RADIOACTIVITY IN THE CAVITY

The RDA proposal estimates of average radioactivity to be expected in the cavity are being repeated in more detail, taking into account the pulsed nature of the source. The results for the fission products are as expected, the activity spike from the last explosion disappearing before the next one. Induced activities are being calculated.

SOLUTION MINING AND STABILITY

Participants in the ARPA Project Payette met at RDA on 29 August 1973 to discuss plans for solution mining a cavity. The present plan is as follows: during the next seven months Fenix and Scisson will solution mine a cylindrical cavity for Transco Oil in the Eminence salt dome. The immediate purpose of this is to check calculations on shrinkage (Woodward and Clyde -- done by K. Nair). If this operation is successful then ARPA, given approval, will use the same drill hole to excavate a spherical cavity at a lesser depth, after closing off the cylindrical cavity.

During the meeting it was disclosed that no liquid filled cavity has shrunk in size. Recent experience with pressurized gas filled cavities in Germany shows shrinkage when the pressure is reduced to about one quarter of the overburden.

WORKING FLUID (THERMAL PULSE)

A qualitative look at the proposed working fluids shows that all but air are transparent to visible radiation up to several thousand degrees. (In fact, methane and sulfur were added to the list, but sulfur is liquid at the operating conditions.) Hot air forms NO_2 which is opaque in the visible.

Using air opacities based on equilibrium NO_2 concentrations, LASL has calculated a very small thermal pulse at the wall. We have verified qualitatively that this result is reasonable, and that the NO_2 reaction rates in this situation are fast enough to keep the air opaque, even though photodissociation can reduce the NO_2 concentration to 20% of its equilibrium.

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IN REPLY
REFER TO: DOS-1-61

August 24, 1973

A PROPOSAL FOR THE DEVELOPMENT OF NUCLEAR DEVICES AS ENERGY SOURCES

As a matter of priority LASL proposes to develop nuclear devices which are optimized to meet possible energy requirements of the future. There are a number of well-founded reasons for such a proposal:

- Nuclear explosives can supply energy at an anticipated cost between $1 and $3 per ton equivalent of TNT over some range of yield. This cost is about the same as that paid for coal.

- The energy density afforded by nuclear explosives is quite large, a fact which facilitates its emplacement.

- The urgency for the proposal is based upon the opinion that the AEC device development capability may well be on the decline. In an era of apparent decreasing military demand, and in the context of a possible Comprehensive Test Ban, the capacity to develop optimized designs based upon present technology or designs based upon new technology could essentially disappear with no prospect for recovery. Thus if there are possible "holes" in our technology, or there are severe restrictions on devices with known application they should be pursued with dispatch.

The requirements placed upon these nuclear explosives will vary with the application. However in considering any specific application cost and radioactive contamination are important factors.

- Cost: In practically every situation minimum device cost is an overriding requirement. In the past the AEC has given serious consideration to this factor; however it has been in a context which placed great emphasis on such features as reliability, optimum configuration, high yield/weight, survival under extreme environmental conditions, long stockpile life, etc. To develop systems in which some of these factors are of far less importance or even ignorable, requires a reorientation which must be made. Another element of cost is associated with the consumption of scarce natural resources. Since some applications could consume large numbers of devices, this factor could become significant; though it is difficult to make a firm case in this regard. The availability of most special nuclear materials can be argued to be almost inexhaustible. However, the cost of some materials will increase significantly as ready deposits are depleted. Certainly deuterium is an inexhaustible and available material.

- Radioactive contamination: All things considered, detonation of a device should result in minimum contamination: fission products, plutonium, tritium, irradiated surroundings.

In the past, LASL has devoted its attention to the development of gas stimulation devices. The first Plowshare experiment, in which the Laboratory participated (Rulison) employed an expensive fission device. Last year (FY 1973) attention was directed to the design of a very cheap, small diameter (9-in.) implosion system. This untested design will be described in a report soon to be published. A summary of this work and plans for further development are included as Annex A. Notable is the proposal for the development of a "tritium free" system.

As a second avenue of investigation we would propose the development of clean, cheap devices. Probable parameter ranges of concern would be the following:

- % fission: 0.1 - 10
- Configuration: minimum restriction
- Fuel: deuterium, ^{6}Li
- Yield range, kt: 1 - 1000.

These conditions would be restricted by a careful and early study of cost, possible applications, our level of understanding of the systems, and a requirement for a high level of safety and security during handling of the device.

Practically all avenues of this investigation have received considerable thought. In most cases it has been supported by calculation, and in many instances, by nuclear test. It remains to complete the proposed study to focus upon those parameter values of greatest interest. Certainly this area of investigation could by itself, easily require the expenditure of 5 million dollars per year.

Needless to say, at the proposed level of activity there will be other currently unthought-of types of devices which will merit attention. LASL would remain flexible to meet such events.

ANNEX A

A REVIEW OF ACTIVITY TO DATE

and

A PROPOSAL FOR FUTURE EFFORT OF NUCLEAR DEVICES FOR NATURAL GAS STIMULATION

FY 1973 Program

The LASL Plowshare effort in FY 1973 was funded at a level of $350,000. This money was expended in the execution of the following tasks:

Task	Cost
1. To act as a center of expertise on all aspects of the Plowshare gas stimulation program.	$ 80K
2. To participate actively in proposals for using nuclear explosives in the Plowshare program, e.g., Rio Blanco II.	$ 15K
3. To carry on active Plowshare stimulation system development program including a nuclear explosive and a full emplacement and firing system.	$255K

Reference 1 defines the effort carried out with respect to Task 2. Reference 2 outlines the report in progress which will review LASL activities with respect to Task 3. The following is an outline of the topics to be reported and a conclusion as presented in reference 2:

1. Fundamental physics designs and trade-offs. Considerable effort has been spent on pit design computations. Tables and curves will be presented showing the trade-off features. (Specific features are classified.)
2. Techniques for internal initiation.
3. The fabrication and assembly costs of the various pit designs will be estimated and compared.
4. HE material studies and high temperature storage tests will be reported. TATB-like explosives appear to be applicable.
5. We have been successful in detonating TATB. Detonator types and tests will be described.

6. We will describe a simple fire set which we have designed. Many of the components exist today.

7. We will list other Plowshare letters, memos, and proposals which have been generated.

Our work to date indicates that we can design small diameter nuclear explosives that will survive environments up to 350°F for extended periods of time without using refrigeration techniques. We are very enthusiastic about pursuing this project and hope that the program will be kept alive in FY 74 at least at the $370K level.

Future Program

The FY 1974 and FY 1975 programs are defined in reference 3. These programs continue the FY 1973 effort to a state of completion. The budget for FY 1974 is estimated at 1.8 million dollars. The FY 1975 budget is estimated at 2.5 million dollars. (The details of these programs are classified; hence they are not reproduced here.)

Clearly this program could be displaced and extended to meet funding levels. It should be added that the proposed levels define a "trouble free" program, which one would associate with a very conservative design. Optimizing the system would almost certainly increase the cost significantly.

One of the foremost problems besetting the nuclear gas stimulation program is that of residual tritium. Present explosives designed for gas stimulation offer a "minimum residual tritium" system. We propose to develop a "tritium free" system, by eliminating tritium and substituting ^{11}Bs as a fuel. Preliminary work at LASL has indicated that it should be feasible to design such a system at a 9-inch diameter. With some neutron shielding the tritium production in the soil could be reduced to negligible amounts. The development cost of such a system would be in excess of 10 million dollars extended over a number of years.

References:

1. DOS-1-16, LASL *Rio Blanco II Proposal*, November 1972.
2. DOS-1-52, LASL Letter Shreffler to Oakley, May 23, 1973.
3. DOS-1-23, LASL Letter Shreffler to Fleming, January 5, 1973.

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IN REPLY
REFER TO: DOS-1-71

October 12, 1973

REPORT OF WORK DONE AT LASL DURING THE MONTH OF SEPTEMBER 1973 IN PACER

The following is a brief summary of the activities carried on by LASL.

LASL efforts have been focused upon program organization, Cavity Phenomenology, Engineering, and Working Fluid. All of these activities are being carried on in close conjunction with RDA. The major advance during the month has been associated with the assignment of water as a working fluid. In the early part of the program it was decided to to direct attention to water until a better choice could be made; now it begins to appear uniquely and eminently qualified. (See RDA report.)

Preparations are being made for a midyear review of the program.

Documents Published:

1. Hubbard to Shreffler, PACER WORKING FLUID AND NEW OPERATION CONDITIONS - Sept. 25, 1973. This document reports on a RDA/LASL meeting at RDA in working fluid and proposes new operating conditions for water working fluid insuring that the fluid will remain in gas phase except for certain positions within the primary loop. Absence of hydrolysis at cavity wall and corrosion with hardware is discussed.
2. Shreffler to Jones, DOS-1-65, Sept. 13, 1973. This letter to Col. Jones (ARPA) expressed PACER interest in the Fennix & Scission/ARPA proposal for Payette experiments in the stability of solution mined cavities in salt domes.

R. G. Shreffler

R. E. Roush

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RDA-MR-4100-003

MONTHLY PROGRESS REPORT

REPORT OF WORK DONE AT RDA DURING THE MONTH OF SEPTEMBER 1973 ON CONTRACT AT(29-2)3324

OCTOBER 1973

By:
H. W. HUBBARD

Sponsored by:

U.S. ATOMIC ENERGY COMMISSION
Washington, D. C. 20545

REPORT OF WORK DONE AT RDA DURING THE MONTH OF SEPTEMBER 1973 ON CONTRACT AT(29-2)3324

RADIOACTIVITY

The study of radioactivity has been completed and a report prepared. The activity expected at the surface is a few tenths of a percent of that produced by conventional reactors producing the same power.

WORKING FLUID

Steam is the present choice for a working fluid. The fears concerning the corrosive properties of the H_2O-NaCl fluid and the formation of NaOH and HCl have been allayed by the experience reported by G. C. Kennedy (UCLA) during a series of tests.

ENGINEERING FEASIBILITY

Jointly with LASL the program elements for this project have been firmed.

Studies of direct steam and steam-liquid systems were continued. Reports are in preparation detailing material weights and probable costs. Feasibility seems assured at significant but not prohibitive costs.

FIREBALL PROBLEMS

Opacity data are still under preparation for the H_2O-air mixture, the air being required to provide NO_2 at elevated temperatures. Only NO_2 among the cheap gases is opaque to visible radiation.

The possibility of using reflected shocks to break up the fireball before it rises was discussed, and some quantitative work is being started.

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UNIVERSITY OF CALIFORNIA
LOS ALAMOS, NEW MEXICO 87544

OFFICE MEMORANDUM

TO : Distribution

DATE: November 21, 1973

FROM : R. G. Shreffler

SUBJECT: OCTOBER 1973 PROGRESS REPORT ON PROJECT PACER.

SYMBOL : DOS-1-77

The progress made on this program during the month of October, 1973 is summarized in the two attachments.

R. G. Shreffler

RGS:rb

Attachments:

1. Monthly Technical Progress Report, H. W. Hubbard, October 1973.
2. Monthly Technical Progress Report, October, R. G. Shreffler/ R. Roush. DOS-1-78

Distribution:

Maj. Gen. E. B. Giller, AGM, USAEC
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V. C. Vespe, ALO
A. Latter, RDA (2)
H. M. Agnew/D. P. MacDougall, LASL Dir
Frank Harlow, LASL T-3
J. Russell, LASL TD-7
D. Venable, LASL M DO
F. Schilling, LASL ENG 6
R. H. Campbell, LASL J-DO
R. Aliro, LASL WX-2
R. N. Thorn, LASL TD DO
ISD-5
DOS File (2)

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IN REPLY
REFER TO: DOS-1-78

November 21, 1973

REPORT OF WORK DONE AT LASL DURING THE MONTH OF OCTOBER 1973 ON PACER

The following is a brief summary of the PACER activities carried on at LASL.

1. Thermonuclear Explosive Design

A document was written with RDA defining the constraints on the thermonuclear explosive design: DOS-1-74, November 1, 1973, "PACER Thermonuclear Explosives Constraints."

2. Cavity Phenemonology:

A. Working Fluid Determination and Evaluation

Experiments are being performed on metals exposed in water at the working temperatures and pressures in order to identify surface corrosion products and their kinetics of formation. The objective is to determine the degree to which the physical properties of the metals are affected. Early experiments done on stainless steel (18-8) confirmed the observations of Kennedy, namely that the corrosion consisted of a thin, durable coat (probably an iron chromate spinel). Experiments are continuing on stainless steel and are beginning on Inconel 625. The latter material looks most promising not only from the point of view of corrosion but with respect to other physical and chemical properties as well.

B. Nuclear Explosion Investigation

Water has been incorporated into the opacity code (ABSCO) in preparation for nuclear explosion calculations (RADFLOW).

C. Calculation of Working Fluid

CIRCO code has been written and test problems successfully run. This code will compute the motion of the working fluid in the cavity under the influence of (1) the nuclear explosion and (2) the exit and entrance of the working fluid from the primary loop.

A report has been written by Eric M. Jones, LA-5427-MS, "PACER Program. A Strong Explosion in a Spherical Cavity: Two Dimensional Evolution." This report described a calculation, using the two-dimensional fireball code YAQUI, which treats a 100 kt explosion in a spherical, air filled cavity of 200 m radius, at typical working conditions (767°K, 0.2027 g/cm^3). It was found that the hot, low density bubble rises at about 18 m/sec. At 12 seconds the bubble is near the top wall and has a temperature of at least 1900°K.

D. Wall Erosion Problem and Cavity Stability

The TSSAS two-dimensional stress code has been adjusted to compute the temperature field in the salt surrounding the cavity and the creep of the cavity walls. Initial computations have been done.

3. Investigation of Engineering Feasibility

Work is continuing concentrating on primary loop design.

4. The program is progressing well. The capabilities of RDA and LASL are ideally suited to such an undertaking.

R. G. Shreffler

R. E. Roush

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RDA-MR-4100-004

MONTHLY PROGRESS REPORT

REPORT OF WORK DONE AT RDA DURING THE MONTH OF OCTOBER 1973 ON CONTRACT AT(29-2)3324

OCTOBER 1973

By:

H. W. HUBBARD

Sponsored by:

U.S. ATOMIC ENERGY COMMISSION
Washington, D. C. 20545

REPORT OF WORK DONE AT RDA DURING THE MONTH OF OCTOBER 1973 ON CONTRACT AT(29-2)3324

CHEMISTRY

The composition of the H_2O and NaCl mixture in the cavity has been computed considering about 25 chemical species at various temperatures and densities for both real and ideal gases. These calculations have been repeated using H_2O plus NaCl plus a few percent air and considering about 40 chemical species.

The effect of condensation and evaporation on the shock at the wall has been estimated and there is no perceptible effect.

ENGINEERING

Three draft documents have been produced concerning:

1. The primary loop high pressure pipe;
2. Pressurized water heat exchangers;
3. All steam heat exchangers.

SAFETY

Some estimates have been made of the seismic effect of the explosion by means of elasto-plastic calculations.

Safety related laboratory experiments have been considered in general outline. These experiments include those bearing both on geologic and engineering materials.

SALT MINE EXPERIMENT

The possibility of conducting a salt dome experiment from an available salt mine has been discussed in some detail and a preliminary report prepared by Rawson Associates. This experiment might serve as an intermediate between the laboratory and the larger salt dome HE experiments.

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OFFICE MEMORANDUM

TO : Distribution

DATE: December 14,1973

FROM : R. G. Shreffler

SUBJECT: NOVEMBER 1973 PROGRESS REPORT ON PROJECT PACER

SYMBOL : DOS-1-84

The progress made on this program during the month of November, 1973, is summarized in the two attachments.

R. G. Shreffler

RGS:rb
Attachments:
1. Monthly Technical Progress Report, H. W. Hubbard, Nov. 1973
2. Monthly Technical Progress Report, November, R. G. Shreffler/ R. E. Roush. DOS-1-85

Distribution:
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A. Latter, RDA (2)
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Frank Harlow, LASL T-3
J. Russell, LASL TD-7
D. Venable, LASL M DO
F. Schilling, LASL ENG 6
R. H. Campbell, LASL J DO
R. Alire, LASL WX 2
R. N. Thorn, LASL TD DO
ISD-5
DOS File

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IN REPLY
REFER TO: DOS-1-85

December 14, 1973

REPORT OF WORK DONE AT LASL
DURING THE MONTH OF NOVEMBER 1973 ON PACER

The following is a brief summary of the PACER activities carried on at LASL.

1. Work reported in some detail in October is continuing.
2. A major effort is being expended with RDA in defining and planning the PACER Phase 1 effort.
3. Presentations were made at AEC Headquarters and at ALO reviewing the PACER effort.
4. The following documents were written:

   November 21, 1973, Shreffler to Distribution. PACER Briefing, DOS-1-80

   November 29, 1973, Hubbard & Shreffler, The Association of the PACER Program and the Nuclear Weapons Program, DOS-1-82.

   November 28, 1973, Constraints on PACER Thermonuclear Explosives, DOS-1-74 (Revised).

R. G. Shreffler

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RDA-MR-4100-005

MONTHLY PROGRESS REPORT

REPORT OF WORK DONE AT RDA DURING THE MONTH OF
NOVEMBER 1973 ON CONTRACT AT(29-2)3324

NOVEMBER 1973

By:
H. W. HUBBARD

Sponsored by:

U.S. ATOMIC ENERGY COMMISSION
Washington, D.C. 20545

REPORT OF WORK DONE AT RDA DURING THE MONTH OF NOVEMBER 1973 ON CONTRACT AT(29-2)3324

SEISMIC PULSE

Calculations have been extended with slightly modified salt properties, with very little change in results; i.e., decoupling of ~ 100.

PLANNING

Considerable effort has been expended in planning the experimental program and follow-on theoretical work to complete Phase I of the PACER program.

ATTENUATION OF SHOCK IN PIPES

Estimates by two different methods lead to the conclusion that the shock from the explosion is reduced to insignificant level after traveling up the pipes to the surface.

ENGINEERING

The overall thermal efficiency of the proposed throttled steam power plant has been investigated in some detail. It is found that the efficiency lies in the range 30% to 32%.

LOS ALAMOS SCIENTIFIC LABORATORY
UNIVERSITY OF CALIFORNIA
LOS ALAMOS, NEW MEXICO 87544

OFFICE MEMORANDUM

TO : Distribution

DATE: January 14, 1974

FROM : R. G. Shreffler

SUBJECT : DECEMBER 1973 PROGRESS REPORT ON PROJECT PACER

SYMBOL : DOS-1-87

The progress made on this program during the month of December, 1973, is summarized in the two attachments.

R. G. Shreffler

RGS:rb
Attachments:
1. Monthly Technical Progress Report, H. W. Hubbard, December 1973.
2. Monthly Technical Progress Report, December, R. G. Shreffler/ R. E. Roush. DOS-1-88

Distribution:
Maj. Gen. E. B. Giller, AGM, USAEC
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V. C. Vespe, ALO
A. Latter, RDA (2)
H. M. Agnew/D. P. MacDougall, LASL DIR
Frank Harlow, LASL T-3
J. Russell, LASL TD-7
D. Venable, LASL M DO
F. Schilling, LASL ENG 6
R. H. Campbell, LASL J DO
R. Alire, LASL WX 2
R. N. Thorn, LASL TD DO
ISD-5
DOS File

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IN REPLY
REFER TO: DOS-1-88

January 14, 1974

REPORT OF WORK DONE AT LASL DURING THE MONTH OF DECEMBER 1973 ON PACER

The following is a brief summary of the PACER activities carried on at LASL.

1. Work reported in some detail in October is continuing.
2. A major effort is being expended with RDA in defining and planning the PACER Phase 1 effort.

R. G. Shreffler

An Equal Opportunity Employer

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RDA-MR-4100-006

MONTHLY PROGRESS REPORT

REPORT OF WORK DONE AT RDA DURING THE MONTH OF DECEMBER 1973 ON CONTRACT AT(29-2)3324

JANUARY 1974

By:
H. W. HUBBARD

Sponsored by:
U. S. ATOMIC ENERGY COMMISSION
Washington, D. C. 20545

REPORT OF WORK DONE AT RDA DURING THE MONTH OF DECEMBER 1973 ON CONTRACT AT(29-2)3324

SAFETY

A possible mechanism for growth of a crack into cold salt has been examined qualitatively. The physical conditions required to start the growth appear to be unlikely since a long initial crack is required, and there are several mechanisms which will stop the growth. It is hoped that some quantitative theoretical study can be made, but in any case, experiments will be designed to elucidate the mechanism.

FIREBALL COOLING

A calculation has been made of the recompression of the fireball by the shock reflected from the cavity wall. Preliminary analysis of the results indicates that considerable mixing will occur--probably more than enough to cool the fireball to nearly ambient conditions.

ENGINEERING

The thermal efficiency study has been completed, and a more thorough study of piping costs has been initiated with the aim of optimizing the cavity depth.

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OFFICE MEMORANDUM

TO : Distribution

DATE: March 25, 1974

FROM : R. G. Shreffler

SUBJECT : JANUARY AND FEBRUARY 1974 PROGRESS REPORTS ON PROJECT PACER

SYMBOL : DOS-1-96

The progress made on this program during the months of January and February 1974, is summarized in the three attachments.

for R. G. Shreffler

RER:rb
Attachments:

1. Monthly Technical Progress Report, H. W. Hubbard, January 1974
2. Monthly Technical Progress Report, H. W. Hubbard, February 1974
3. Monthly Technical Progress Report, R. G. Shreffler, DOS-1-97

Distribution:
Major General E. B. Giller, AGM, USAEC
E. Fleming, DAT, USAEC
F. C. Gilbert, DMA, USAEC
H. C. Donnelly, ALO
D. K. Nowlin, ALO (2)
V. C. Vespe, ALO
A. Latter, RDA (2)
H. M. Agnew, D. P. MacDougall, LASL DIR 100
Frank Harlow, LASL T-3 216
D. Venable, LASL M-DO 682
F. Schilling, LASL ENG-6 310
R. H. Campbell, LASL J-DO 665
R. Alire, LASL WX-2 920
R. N. Thorn, LASL TD-DO 218
ISD-5
File

RDA-MR-4100-007

MONTHLY PROGRESS REPORT

REPORT OF WORK DONE AT RDA DURING THE MONTH OF JANUARY 1974 ON CONTRACT AT(29-2)3324

FEBRUARY 1974

By:

H. W. HUBBARD

Sponsored by:

U. S. ATOMIC ENERGY COMMISSION
Washington, D.C. 20545

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REPORT OF WORK DONE AT RDA DURING THE MONTH OF JANUARY 1974 ON CONTRACT AT(29-2)3324

PROJECT 2

Studies of CO_2 as a backup working fluid were begun.

PROJECT 3

Engineering optimization studies are being continued, i.e., piping costs and thermal efficiency variation with the use of working fluids other than steam have been calculated.

PROJECT 9

A continued effort was made to estimate Phase I costs.

RDA-MR-4100-008

MONTHLY PROGRESS REPORT

REPORT OF WORK DONE AT RDA DURING THE MONTH OF FEBRUARY 1974 ON CONTRACT AT(29-2)3324

MARCH 1974

By:

H. W. HUBBARD

Sponsored by:

U. S. ATOMIC ENERGY COMMISSION
Washington, D. C. 20545

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REPORT OF WORK DONE AT RDA DURING THE MONTH OF FEBRUARY 1974 ON CONTRACT AT(29-2)3324

PROJECT 2

The effect of repeated shock reflections and fireball recompression has been estimated through an extension of the machine rad-hydro calculations made in December 1973.

PROJECT 5

Some new calculations were made of the seismic response of salt to a more realistic pressure pulse. Equation of state variations are being undertaken.

PROJECTS 4 AND 6

Some consideration is being given to the economics and conceptual layout of lined rock cavity systems incorporating plutonium breeding.

PROJECT 7

Criteria are being established for sites.

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IN REPLY
REFER TO: DOS-1-97

March 25, 1974

REPORT ON WORK DONE AT LASL DURING THE MONTHS OF JANUARY AND FEBRUARY 1974 ON PACER

LASL efforts on PACER have been devoted to developing and testing phenomenology codes and further defining and organizing Phase 1 of the program. A meeting with RDA, ALO and LASL people was held on February 22. The list of attendees and an agenda are attached. The following documents are also attached:

1. DOS-1-92,"Some Cavity Stability Implications on the Use of Water as the Working Fluid for PACER Power Generation," A. W. Nutt.
2. "The PACER Project: Determination of Circulation Patterns in a Spherical Cavity," L. M. Simpson, T. D. Butler and F.H. Harlow.
3. RDA-JTR-41-0-1, "Preliminary Material Evaluation, Pre-Test Report for PACER Program, N. F. Kfoury and A. W. Nutt.

for R. G. Shreffler

Attendees at PACER Meeting on February 22 at LASL

RDA

Harmon Hubbard
Arlen Field
Forrest R. Gilmore
Linn A. Gore
David Griggs (Consultant)
R. Philip Hammond
Nicholas F. Kfoury
Don E. Rawson (Consultant)

AEC

Harry Fish
John A. Malmstrom
Charles B. Quinn
Richard E. Torres
Harry A. Weber
A. E. Whiteman

LASL

H. M. Agnew
George Allshouse
C. A. Anderson
Fred N. App
Mike Antal
W. D. Barfield
J. F. Barnes
M. L. Brooks
R. R. Brownlee
Robert Canada
Terry R. Gibbs
Paul M. Giles
F. H. Harlow
W. F. Heubner
Lew Jones
Charles F. Keller
Jerry J. Koelling
Andy Koence
Ellen Leonard
D. P. MacDougall
Larry Madsen
T. J. Merson
A. W. Nutt
Eldon Pequette
George S. Price
R. E. Roush
Fred P. Schilling
Tom Scolman
Robert R. Sharp
R. G. Shreffler
Louis C. Smith
Rodney S. Thurston
John Zinn

PACER REVIEW
Friday, February 22, 1974
Green Room (D-115)
Los Alamos Scientific Laboratory

The times allotted include both presentation and discussion

8:15	Introductory Remarks	R. Shreffler	(10 min)

Program Review

8:25	1. Thermonuclear Device	R. Roush	(15 min)
	2. Cavity Phenomenology		
8:40	2.1 Working Fluid	A. Nutt	(5 min)
8:45	2.2 Nuclear Explosion Investigation (t<1 sec)	H. Hubbard	(10 min)
		E. Martinelli	(10 min)
		F. Gilmore	(10 min)
		LASL activities	(10 min)
9:25	2.3 Circulation of Working Fluid (t>1 sec)	L. Simpson	(30 min)
9:55	2.4 Cavity Integrity--Creep Effects	C. Anderson	(30 min)
10:25	Break		(10 min)
10:35	3. Engineering		
	3.1 Engineering Project Coordination	T. Merson	(10 min)
	3.2 Primary Loop 3.3 Materials	L. Gore	(10 min)
	3.4 Containment 3.5 Injection	T. Merson	(10 min)
11:05	4. Economics	H. Hubbard	(5 min)
11:10	5. Safety and Environmental	H. Hubbard	(30 min)
11:40	6. Debris Processing	P. Hammond	(15 min)
11:55	Lunch		
1:00	7. Site Selection, Cavity Engineering	R. Sharp/D. Rawson	(30 min)
1:30	8. Nuclear Site Definition	General Discussion	(30 min)
2:00	9. Management, Systems and Planning	H. Hubbard/ R. Shreffler	(5 min)

Experiment Review

2:05	1. Material Selection	A. Nutt	(20 min)
2:25	2. Halite and Anhydrite Creep Rupture	C. Anderson	(10 min)
2:35	3. Primary Loop Mockup	T. Merson	(10 min)
2:45	4. Shaft Sealing	T. Merson	(10 min)
2:55	5. Device Injection	T. Merson	(10 min)
3:00	Break		(15 min)
3:15	6. Dynamic Loading at Access Piping	R. Roush	(15 min)
3:30	7. Opacity of Working Fluid	L. Jones	(15 min)
3:45	8. Laboratory Cavity	L. Gore	(15 min)

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IN REPLY
REFER TO: DOS-1-92

February 25, 1974

SOME CAVITY STABILITY IMPLICATIONS ON THE USE OF WATER AS THE WORKING FLUID FOR PACER POWER GENERATION

A. W. Nutt

Water, mixed with a few percent air, is the prime candidate PACER working fluid. The purpose of this interim communication is to summarize pertinent literature and to address potential cavity instability problem areas which may arise from the use of water as the PACER working medium.

The H_2O-NaCl Binary

The literature most germane to the PACER proposal is "The System H_2O-NaCl at Elevated Temperatures and Pressures," by S. Sourirajan and G. C. Kennedy(1). Sourirajan and Kennedy reviewed previous work(2-4) and confirmed the three-phase (NaCl solid, liquid, gas) vapor pressures in the NaCl-H_2O system at the operating temperatures (525-550°C) and pressures (320 ± 22 bars) of interest to the PACER program. See Fig. 1.

The presence of excess salt from the salt dome containment cavity creates an automatic pressure-buffer, which guarantees a maximum pressure at 525°C of ∿ 340 bars. In any circumstances, the maximum pressure which can be obtained is ∿ 380 bars (at ∿ 575°C). Any attempt to create a cavity pressure greater than that allowed by the three-phase-boundary curve in Fig. 1 (e.g., addition of excess water or the explosion of a nuclear device) will result in liquid formation whose composition is given in Fig. 2. The PACER working fluid cavity therefore behaves as a self-limiting pressure source having inherent safety.

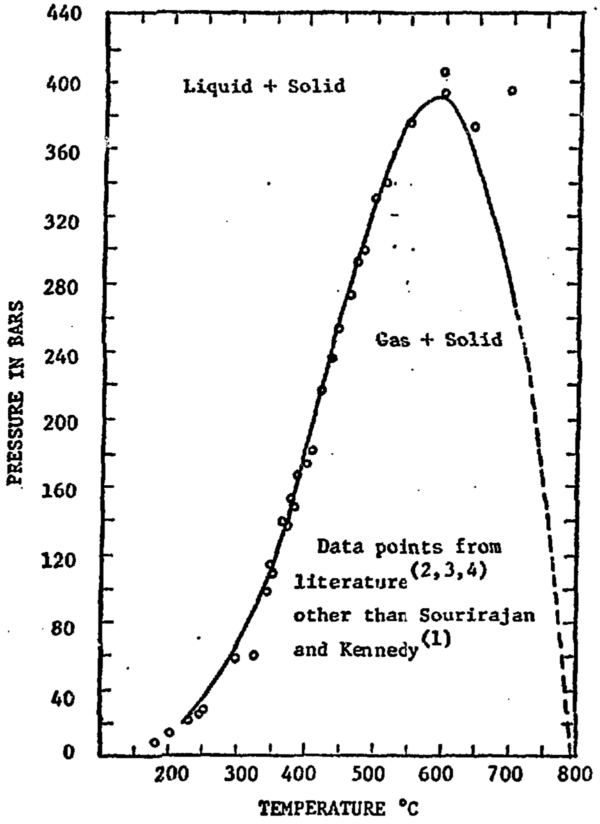

Fig. 1. Three-phase vapor pressures in the binary H_2O-NaCl system, after Sourirajan and Kennedy(1).

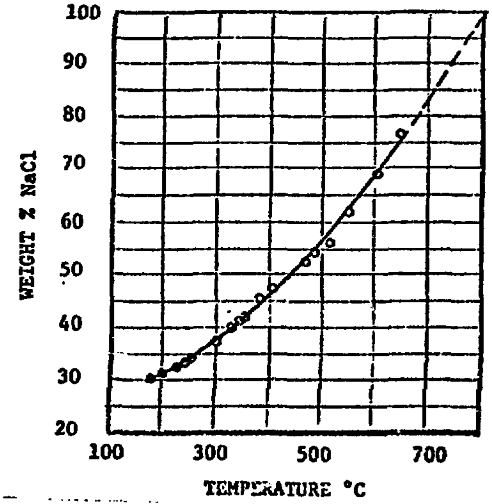

Fig. 2. Composition of the liquid phase of saturated aqueous sodium chloride solutions. Data from Keevil.(2)

Chemical Stability of the Salt Dome Cavity

NaCl has been found to undergo the hydrolysis reaction $NaCl_{(s)} + H_2O_{(v)} \rightleftarrows NaOH_{(s\ or\ l)} + HCl_{(g)}$ at temperatures in excess of 275°C. The low temperature limit for salt hydrolysis was established after several authors hypothesized that the reaction was important in the epitaxial growth of metal single crystals on rock salt.(5) The formation of NaOH in NaCl crystals exposed to water vapor in air or Ar at temperatures of 500-720°C was established by appearance of cavities(6) and by optical absorption.(7,8) The extent of the salt hydrolysis reaction has been studied from 600-950°C.(9) As a result of these studies, we wondered whether the hydrolysis reaction of NaCl in the PACER cavity would create hydroxyl ions that could diffuse (probably via grain boundaries) into the salt and produce low melting (< 500°C) compounds of $NaOH \cdot xH_2O$ or $(NaCl)_x \cdot (NaOH)_y$ between grains. Our concern was that these low melting compounds would reduce the grain boundary viscosities and produce flow and spallation of the salt dome which is not indicated by creep calculations.(10)

After careful examination of published data, we have concluded that the salt dome cavity will not undergo significant hydrolysis at the gas-solid interface. Sourirajan and Kennedy(1) reported no detectable pH differences in either the liquid or gaseous phases near the critical pressures of any composition in the $NaCl-H_2O$ system (pressures and temperatures greater than proposed for PACER). Any hydrolysis reaction would have produced acidic gases and basic liquids. Subsequent discussions with Kennedy(12) confirmed that no significant hydrolysis reactions could be expected under equilibrium conditions.

The above conclusions are corroborated from two additional sources. Hanf and Sole(9) report that equilibrium in the $NaCl-H_2O$ system is attained rapidly even when the NaCl is solid. This observation lends further creditability to the Sourirajan and Kennedy data and conclusions. Finally, R. G. Lindgren(12) thermodynamically calculated the amount of hydroxyl ion present under the proposed PACER cavity conditions. These calculations predict condensed phase hydroxyl ion concentrations on the order of 10^{-10} mole fractions, an insignificant amount.

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10. Private Communication, C. A. Anderson (LASL) Meeting at LASL, 22 February 1974.

11. Private Communication, G. C. Kennedy, Consultant, meeting at R&D Associates, 21 September 1973, Santa Monica, CA.

12. Private Communication, R. G. Lindgren (RDA)to A. W. Nutt (LASL), 28 September 1973.

The PACER Project: Determination of Circulation Patterns in a Spherical Cavity (L. M. Simpson, T. D. Butler, and F. H. Harlow)

The PACER program introduces a new concept of producing electrical power from thermonuclear energy. In this concept energy is released from periodic thermonuclear explosions in an underground cavity in a salt dome. This cavity is filled with a working fluid such as water, which is heated by the released energy. The thermal energy in the working fluid is transferred underground to another fluid through a heat exchanger, and pumped to the surface for conversion.

Currently, various facets of this concept are being investigated to determine its feasibility. For instance, in order to determine the ideal placement and pumping requirements for the heat exchangers, the circulation patterns of the working fluid must be investigated. This study has been undertaken by Group T-3, and for this purpose, the CIRCO code has been developed.

CIRCO is a two-dimensional computer program based on the MAC technique.[1] In cylindrical coordinates, it calculates the circulation patterns of the working fluid in the cavity. Azimuthal symmetry is assumed. The full Navier-Stokes equations for the fluid flow are coupled with a heat transport equation and are solved by a high-speed computer to obtain results that we display for an r-z plane. In CIRCO, circulation of the working fluid can be initiated in three ways:

1. From the bouyancy induced by a localized hot region, which is the result of the non-uniform distribution throughout the working fluid of heat from each explosion,

2. From the bouyancy induced by the removal of heat from the working fluid through heat exchangers,

3. From forced convection induced by the withdrawal of the heated working fluid into heat exchangers and the return of the cooled fluid back to the cavity.

Through use of computer generated plots of solutions of the fluid flow and heat transport equations, the effects of these circulation-inducing mechanisms can be studied. Two sets of representative results are displayed in Figures 1 and 2.

The first study examines the results of bouyancy from the uneven distribution throughout the fluid of energy from an explosion, in the absence of heat exchangers and forced convection. To represent the initial conditions, a heated spherical region of radius 50 m with a temperature of 600°K is located on the axis 75 m from the bottom of the spherical cavity, whose radius is 200 m. The initial temperature of the surrounding fluid is 500°K. As the bouyant fluid rises, a clockwise circulation of the fluid is produced. Gradually the temperature of the initially heated fluid decreases, the bouyant fluid hits the top of the cavity and the circulation slows down. The initial conditions and these time-varying results are illustrated in the sets of plots in Fig. 1. Each time-defined set includes three plots: a velocity vector plot on the left, a temperature contour (isotherm) plot in the center and a pressure contour (isobar) plot on the right. The initial conditions are shown in Fig. 1a. Initially the velocities are zero, thus, the empty vector plot. The heated fluid is represented by the small region in the isotherm plot; whereas, the pressure gradients are shown in the isobar plot. The set of plots in Fig. 1b illustrates the results at a time of 20.0 sec. At this time the induced circulation, as indicated in the velocity vector plot, is clockwise. The magnitude of the maximum velocity in the system, V_{max}, is 16.9 m/sec. By this time the maximum temperature, T_{max}, is 576.8°K. Associated with the vortex center of the circulation is a low pressure region; whereas, a high pressure region develops at the top of the heated region. In the isobar plot these regions are designated by L and H. The heated fluid continues to rise until, by a time of 40.0 sec, it has reached the top of the cavity. Results for this time are shown in Fig. 1c. A clockwise circulation is still maintained; however, V_{max} is 14.1 m/sec. The value of T_{max} at this time is 520.5°K. The low pressure region is till associated with the vortex center of the circulation. At a time of 70.0 sec the motion of the fluid has slowed down considerably; V_{max} is 4.6 m/sec. The heated fluid is now following the cavity wall. It has cooled to a T_{max} of 510.9°K. The low pressure region remains closely associated with the vortex center. These results are represented in Fig. 1d.

As an extension of the first study the second calculation examines the effects of the withdrawal and the return of the working fluid on the motion of the same initially heated sphere. The initial configuration is indistinguishable from that in Fig. 1a. The working fluid is withdrawn from the equator of the cavity at a velocity of 0.25 m/sec and is returned through the top of the cavity at a velocity of 20.0 m/sec. These velocities are chosen such that the flux of fluid, in and out, is the same, that is, 18,840 m^3/sec, a rate that is very large in order to illustrate especially well the capability of the computer code. The results of this calculation are illustrated in Fig. 2. For comparison purposes the same times are depicted as the first study. The sets of plots are again composed of a velocity vector plot, an isotherm plot and an isobar plot. By a time of 20.0 sec two circulation patterns have developed, as shown in the velocity plot in Fig. 2a.. The counterclockwise circulation is created by the forced convection from the removal and return of the working fluid. The clockwise circulation is induced by the rising buoyant hot fluid. By this time the position of the initially heated fluid is approximately the same as in Fig. 1b. This indicates that the influence of the counter-circulation has not yet been felt. The value of T_{max} is 574.2°K. A low pressure region, as before, follows the vortex center of the circulation induced by the heated fluid. At a time of 40.0 sec the influence of the counter-circulation is clearly manifested. These effects are shown in Fig. 2b. The hot spot rise rate has appreciably decreased and the effects of the counterclockwise circulation are significant. In fact at this time the hottest fluid has been displaced laterally, away from the axis. The value of T_{max} is 519.3°K. Again a low pressure region has followed the lower vortex center. Figure 2c presents the plots for a time of 70.0 sec. At this time the lower vortex has become insignificant, and the counterclockwise circulation has become dominant. Some of the heated fluid has been caught in the counterclockwise circulation while the rest is moving along the wall. The value of T_{max} is 508.6°K. At each of these times the value of V_{max} is the inflow velocity, 20.0 m/sec.

These studies illustrate the usefulness of CIRCO for predicting the motion of the working fluid under various conditions, and indicate the scope of parameter variations that can be investigated. Numerous additional calculations will be performed to study the effects of variations in engineering design that need to be tested for optimizing this type of possible energy source.

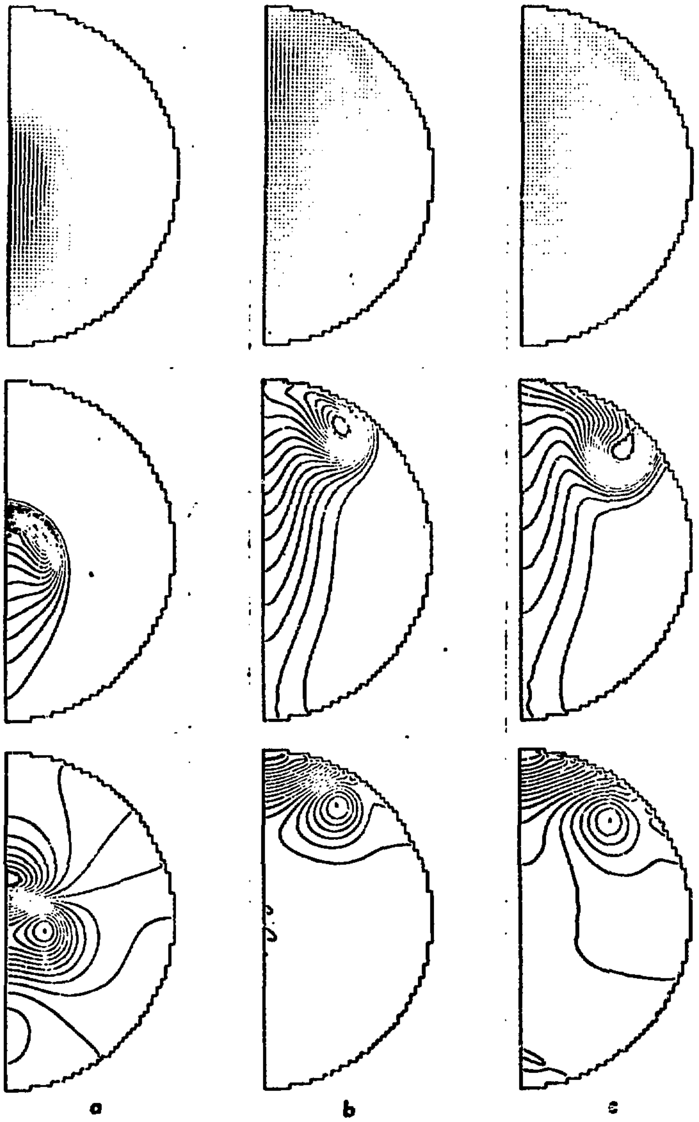

Fig. 1. These figures depict the time-varying results of the circulation induced by a hot bouyant fluid. In each column the figures are arranged with the velocity vector plot on top, the isotherm plot in the center and the isobar plot on the bottom. Each set of plots represents a different time: a. t = 20.0 sec, b. t = 50.0 sec

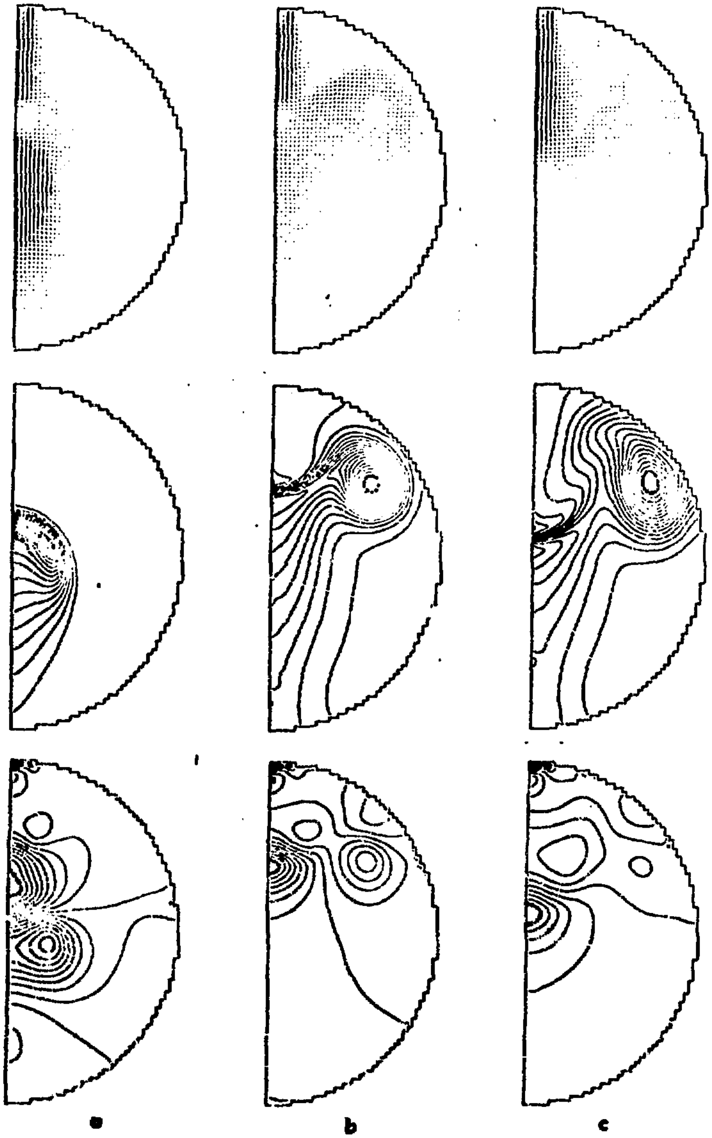

Fig. 2. Presented in these figures are the results of forced convection induced by the withdrawal and return of fluid and the circulation induced by a hot bouyant fluid. The plots are arranged as in Fig. 1. In each column the figures depict a different time: a. t = 20.0 sec, b. t = 50.0 and c. t = 70.0 sec.

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IN REPLY
REFER TO: DOS-1-110

April 24, 1974

REPORT ON WORK DONE AT LASL DURING THE MONTH OF MARCH, 1974 ON PACER

LASL efforts on PACER have been devoted to pursuing the program as stipulated in DOS-1-81. A number of summarizing documents are being written. Particular attention was given to Project 8, Nuclear Test and Effects Facility. Preparations were made by both LASL and RDA for a budget presentation at Germantown early in April.

LOS ALAMOS SCIENTIFIC LABORATORY
UNIVERSITY OF CALIFORNIA
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OFFICE MEMORANDUM

TO : Distribution

DATE: May 17, 1974

FROM : R. G. Shreffler

SUBJECT : APRIL 1974 PROGRESS REPORTS ON PROJECT PACER

SYMBOL : DOS-1-112

The progress made on this program during the month of April, 1974, is summarized in the two documents attached.

R. G. Shreffler

RGS:rb
Enc: RDA Monthly Progress Report, RDA-MR-4100-010, May, 1974
LASL Monthly Progress Report, DOS-1-113, May 17, 1974

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IN REPLY
REFER TO: DOS-1-113

May 17, 1974

REPORT ON WORK DONE AT LASL DURING THE MONTH OF APRIL, 1974 ON PACER

LASL has been preparing summary reports on the following subjects:

TSAS Calculations On Cavity Stability
CIRCO Code development
Engineering.

The initial issue of DOS-1-81, "PACER Program, Phase I, Theoretical and Laboratory Studies," was published. FY 75 budgets were prepared.

R.G. Shreffler

RDA-MR-4100-010

MONTHLY PROGRESS REPORT

REPORT OF WORK DONE AT RDA DURING THE MONTH OF APRIL 1974 ON CONTRACT AT(29-2)3324

MAY 1974

By:

H. W. HUBBARD

Sponsored by:

U. S. ATOMIC ENERGY COMMISSION
Washington, D. C. 20545

R & D ASSOCIATES
Post Office Box 3580
Santa Monica,
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REPORT OF WORK DONE AT RDA DURING THE MONTH OF APRIL 1974 ON CONTRACT AT(29-2)3324

PROJECT 2 - CAVITY PHENOMENOLOGY

2.1 Working Fluid

Work has continued on CO_2 as a backup working fluid.

2.2 Nuclear Explosion

The fireball mixing problem has been examined assuming a density gradient at the edge of the fireball, and assuming incompressible flow. These results indicate instability at wavelengths below a few meters.

PROJECT 9 - SYSTEM ANALYSIS, COORDINATION AND PLANNING

A briefing was given jointly with LASL for DMA and DAT presenting current views and projected requirements. Further estimates have followed this briefing corresponding to various funding levels for FY75.

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OFFICE MEMORANDUM

TO : Distribution

DATE: April 24, 1974

FROM : R. G. Shreffler

SUBJECT : MARCH 1974 PROGRESS REPORTS ON PROJECT PACER

SYMBOL : DOS-1-109

The progress made on this program during the month of March 1974 is summarized in the two documents attached.

R. G. Shreffler

RGS:rb
Enc: RDA Monthly Progress Report, RDA-MR-4100-009, April 1974
LASL Monthly Progress Report, DOS-1-110, April 24, 1974
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RDA-MR-4100-009

MONTHLY PROGRESS REPORT

REPORT OF WORK DONE AT RDA DURING THE MONTH OF MARCH 1974 ON CONTRACT AT(29-2)3324

APRIL 1974

By:

H. W. HUBBARD

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Washington, D.C. 20545

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REPORT OF WORK DONE AT RDA DURING THE MONTH OF MARCH 1974 ON CONTRACT AT(29-2)3324

PROJECT 2 - CAVITY PHENOMENOLOGY

2.1 Working Fluid

Preliminary estimates have been made of engineering suitability of CO_2 as a backup to H_2O. Thermal efficiency is about 3/4 that of the H_2O system.

2.2 Nuclear Explosion

A preliminary investigation of the effect of the radiation heat pulse into salt was begun. The deposition length is treated as a parameter.

PROJECT 3 - ENGINEERING

3.1 Trade Studies

Analytical expressions for the cost of piping, cavity construction, and containment were developed as functions of cavity pressure and volume.

PROJECT 5 - SAFETY AND ENVIRONMENT

5.1 Safety Implications

Containment and quenching systems are being considered for PACER, to prevent venting any steam even if a leak should occur.

PROJECT 6 - FUEL RECOVERY AND PROCESSING

6.3 Production of ^{233}U from Thorium

It has been pointed out that PACER-produced ^{233}U has no gamma ray hazard. It can, therefore, be treated as ^{235}U and diluted with natural U, thus greatly reducing the hijacking-homemade bomb threat.

PROJECT 9 - SYSTEM ANALYSIS, COORDINATION AND PLANNING

Minimization of cost of electricity studies push the system in the direction of large, low pressure cavities. Practical constraints have dictated the present compromise of 200 bars at 1200 meters depth, $Y = 50$ kT for 2000 Mwe.

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OFFICE MEMORANDUM

TO : Distribution

DATE: June 11, 1974

FROM : R. G. Shreffler

SUBJECT : MAY 1974 PROGRESS REPORTS ON PROJECT PACER

SYMBOL : DOS-1-114

The progress made on this program during the month of May, 1974, is summarized in the two documents attached.

Robert Shreffler
R. G. Shreffler

RGS:rb
Enc: RDA Monthly Progress Report, RDA-MR-4100-011, June 1974
LASL Monthly Progress Report, DOS-1-113, June 11, 1974.

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IN REPLY
REFER TO: DOS-1-115

June 11, 1974

REPORT ON WORK DONE AT LASL
DURING THE MONTH OF MAY, 1974, ON PACER

LASL has been preparing summary reports on the following subjects:

TSAS calculations on cavity stability
CIRCO code development
Engineering
PACER site criteria and selection
PACER Thermonuclear Device - preliminary description and goals.

R. ~~G.~~ Shreffler

RDA-MR-4100-011

MONTHLY PROGRESS REPORT

REPORT OF WORK DONE AT RDA DURING THE MONTH OF MAY 1974 ON CONTRACT AT(29-2)3324

JUNE 1974

By:
H. W. HUBBARD

Sponsored By:

U. S. ATOMIC ENERGY COMMISSION
Washington, D. C. 20545

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REPORT OF WORK DONE AT RDA DURING THE MONTH OF MAY 1974 ON CONTRACT AT(29-2)3324

PROJECT 2 - CAVITY PHENOMENOLOGY

2.1 Working Fluid

Report on CO_2 completed. The proposed system obtains some work from the CO_2 before it is sent through a heat exchanger.

PROJECT 9 - SYSTEM ANALYSIS, COORDINATION AND PLANNING

A joint LASL-RDA briefing was given for the Assistant General Manager for Energy and Development Programs.

Planning has been initiated for better cost estimates of cavity construction in hard rock at NTS. In addition, information will be gathered on the availability of experimental salt dome sites in Arizona and the southeast.