ENCLOSURE 1

TENNESSEE VALLEY AUTHORITY

SEQUOYAH NUCLEAR PLANT

RESEARCH PROGRAM

ON HYDROGEN COMBUSTION AND CONTROL

QUARTERLY PROGRESS REPORT

DECEMBER 15, 1980

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I. Introduction

This report is the first of a series of quarterly research summaries presented to the Nuclear Regulatory Commission (NRC) by the Tennessee Valley Authority (TVA) to satisfy the following condition of the Sequoyah Nuclear Plant unit 1 operating license:

> During the interim period of operation, TVA shall continue a research program on hydrogen control measures and the effects of hydrogen burns on safety functions and shall submit to the NRC quarterly reports on that research program.

TVA is pleased to document the various facets of its current degraded core research program in this report and is confident that all possible efforts have been exerted to ensure the timeliness, effectiveness, and completeness of the program. Increased attention was devoted to accidents beyond the design basis in early 1980 as TVA, with the aid of Westinghouse and three architect-engineering firms, produced a report that has since been submitted to the NRC on September 2, 1980, as Volume I of the Sequoyah Nuclear Plant Degraded Core Program Report. TVA has remained in the forefront of industry efforts in many areas of degraded core research and development. This leadership was demonstrated by the decision to voluntarily implement the interim distributed ignition system at Sequoyah to extend the plant's capability for hydrogen control. TVA has continued to voluntarily conduct its own degraded core programs and to cooperatively participate with other utility groups in these research efforts. These efforts are the subject of the present report. The format is designed to present in Section II a summary of the scope, schedule, and status of each task with further technical details in appropriate appendices.

In addition, a summary of the TVA position on equipment survivability for hydrogen burning during degraded core events is presented in Appendix B. TVA firmly believes that the equipment survivability issue is generic and not limited to ice condenser containments. If anything, the equipment within an ice condenser containment could withstand a hydrogen burn better than in a dry containment due to the heat removal potential inherent in the ice bed and structural heat sinks. Appendix B includes a list of key equipment inside the Sequoyah containment, estimates of environmental conditions resulting from hydrogen combustion, and an evaluation of their effects on such equipment.

A brief discussion of studies to scope the potential of carbon dioxide as a postaccident inerting agent is presented in Appendix C.

II. Task Description, Schedule, and Status

The major emphasis of TVA's current research program is to discover, collect, and evaluate enough information about degraded core events and potential mitigations for their risk reduction to be able to select, design, and install a permanent hydrogen control system for Sequoyah Nuclear Plant. This permanent system would satisfy the following condition of the unit 1 operating license:

> For operation of the facility beyond January 3 1982, the Commission must confirm that an adequate hydrogen control system for the plant is installed and will perform its intended function in a manner that provides adequate safety margins.

A list of the most important topics where further information is needed is shown in Table 1. Another list showing both TVA's current major tasks and its outside consultants and resources is presented in Table 2. Figure 1 shows a schedule of activities necessary to meet the unit 1 licensing conditions.

This section provides a summary of each individual or group effort in which TVA is actively involved that is related to hydrogen combustion and control, risk assessment, or overall degraded core studies. Here, the current scope, schedule, and status of each effort is summarized with further details presented in the appendices. Note that certain related risk assessment studies for the Browns Ferry Nuclear Plant are also described, since experience with these techniques will be useful in Sequoyah risk studies.

Table 1

Information Needed to Decide on Final Mitigation

1. Halon feasibility study completed. Conceptual design and preliminary safety evaluation done, if feasibility study is positive.

2. Catalytic combustor feasibility study completed. Preliminary design and safety evaluation done, if feasibility study is positive.

3. New igniter development program completed.

4. Study on electromagnetic interference (EMI) effects of spark igniters completed.

5. Evaluation of additional potential mitigations such as spray fogging and postaccident inerting completed.

6. Best possible decision on design basis accident scenario(s) made.

7. Preliminary MARCH runs completed inhouse on Sequoyah model.

8. Time-dependent hydrogen source term reasonably assured.

9. CLASIX modifications done. New plant specific cases run, if

necessary.

10. Reasonable assurance that any potential hazards from operation or misoperation of the final system are understood.

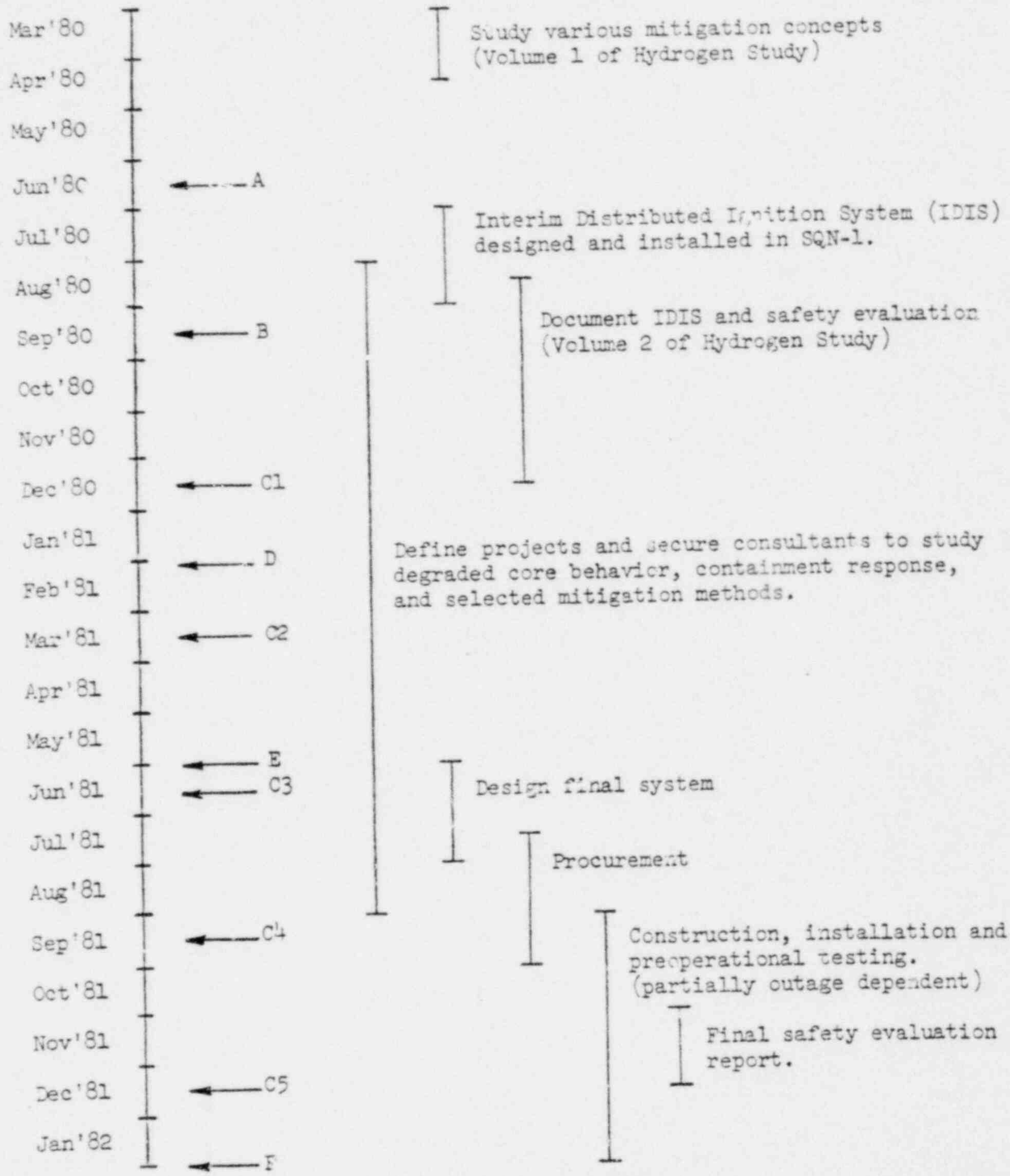
11. Estimate true risk reduction benefit of final mitigation.

Table 2

Major Tasks and Outside Consultants/Resources

Major Tasks	Outside Consultants/Resources
Risk assessment	Kaman Sciences Corporation Pickard, Lowe, and Garrick
Consequence analysis	Batelle, Columbus Laboratory Oak Ridge National Laboratory
Containment response	Westinghouse Offshore Power Systems
State-of-technology research and rulemaking	Atomic Industrial Forum
Igniter development	EPRI (Rockwell-Rocketdyne)
Combustion research	EPRI (AECL-Whiteshell)
Hydrogen control (Halon, fogging)	EPRI (Acurex)
Hydrogen mixing and	EPRI (Hanford Engineering

distribution	Development Laboratory)
Igniter combustion tests	Fenwal
Halon development	Atlantic Research Corporation
Spark igniter development (electromagnetic interference)	Keiser Engineering



Legend:
A: TVA Degraded Core Task Force established
B: SQN-1 Full power license awarded
C: NRC quarterly reports due
D: First Licensing condition cleared
E: Decision for final fix
F: All licensing conditions cleared

Figure 1

A. Atomic Industrial Forum (AIF) Proposal

A.1 Scope

The scope proposal includes the following 15 tasks:

1. Safety Goal/Criteria Application

   a. Generate position paper on the role of safety goal/criteria in the degraded core rulemaking activities

   b. Generate comprehensive criteria for methods for evaluation of degraded core conditions

2. Selection of Dominant Sequences

   a. Initial definition of "likely" dominant sequences based on available material, an initial ranking of sequences in terms of probability and consequences and a definition of currently available preventive and mitigative (e.g., containment heat removal) systems

   b. Quantify the dominant sequences defined in "a", identify any other sequences that should be considered, provide preliminary consequence assessments, and document the process and rationale for selection of dominant sequences

c. Update to include detailed study results such as the ones for Zion-Indian Point, NSAC/Duke, Limerick, TVA, etc.

3. Identification of Phenomenological and Containment Transient Critical Sequences

General containment phenomenological event trees (or equivalent) for the major reactor systems.

4. Steam Overpressure Phenomena (In-Vessel, Containment)

Provide sound phenomenological models for:

a. The progression of core melt for the identified dominant sequences

b. The conditions necessary for occurrence of steam explosions and effects of resultant explosions

c. Mixing dynamics of core debris-water interactions

d. Steam generation rates for core debris-water interactions and the dynamic effects of large scale core debris-water interactions on the materials involved given typical reactor plant geometries.

5. Hydrogen Generation and Burn

Provide sound phenomenological models for the generation, distribution, iginition, and combustion of hydrogen

6. Hydrogen Burn Control

a. Survey of hydrogen detectors

b. Evaluation of preinerting for containments not already evaluated

c. Evaluation of fogging/spray suppression

7. Equipment Survivability for the Degraded Core Environment

For five plant configurations (BWR, each NSSS vendor PWR, and ice condenser)

a. Identify the minimum set of functions which must be performed or equipment which must not operate as a consequence of the environment to permit termination of core degradation sequences or to monitor the status of the plant and retain containment.

b. Based on "a," identify necessary minimum set of generic equipment.

c. Identify environments associated with the dominant sequences.

d. Evaluate the survivability of the equipment in "b" for the conditions in "c" and define tests, if necessary.

e. Develop recommendations on equipment

survivability criteria and document results of complete task.

8. Core Debris Coolability

Provide technically sound, phenomenological models for the progression of postulated core melt for the dominant containment sequence events.

9. Containment Structural Capability

a. Schedule a seminar of utilities and associated consultants who have performed realistic analyses of containment capability to identify what has been done, what residual work may remain, and what criteria should be proposed by the industry for these evaluations.

b. Define the inertial loadings which may be encountered (from Tasks 6 and 15) and specify the program of analysis of containment inertial load capability for performance.

10. Evaluation of Liquid Pathway Dose

Integrate available information and provide scoping information on the feasibility time span and cost of source interdiction.

11. Fission Product Liberation and Removal

EPRI and DOE are pursuing the development of a program to improve the models currently used to estimate the amount of material liberated and the depletion of this material prior to reaching the population. The intent is to integrate the results of that program into the development of the industry positions on degraded core.

12. Vented Containment Systems

Define the range of applicability of vented containment systems and maintain awareness of alternative pressure reduction systems.

13. Core Ladle

Identify the advantages and disadvantages, real contributions to risk reduction (positive, negative, neutral) and impacts of addition of this feature.

14. Residual Risk Reduction Evaluation

Provide the capability to baseline a limited number (2-4) of plants using detailed PRA studies (e.g., Zion-Indian Point, NSAC/Duke, Limerick) and do risk tradeoff evaluations of alternative preventive or mitigative features and risk sensitivities of key phenomenological issues (e.g., H burn, steam pressure).

15. Integrated Model Definition and Analysis

Provide the integrated analyses of the dominant sequences for representative plants and integrate the models developed in the previous tasks into this integrated analysis. This will include the following tasks:

a. Define MARCH/CORRAL Use

Summarize current experience with MARCH/CORRAL application.

b. Containment Analyses

Perform analyses for representative containment/system types for dominant accident sequences and necessary variants.

c. MARCH/CORRAL Improvements

Define program for improving MARCH/CORRAL models and implement, if desired.

d. Integrate Phenomenology Models into Analyses

Include the results of the phenomenological development activities into the integrated transient analysis.

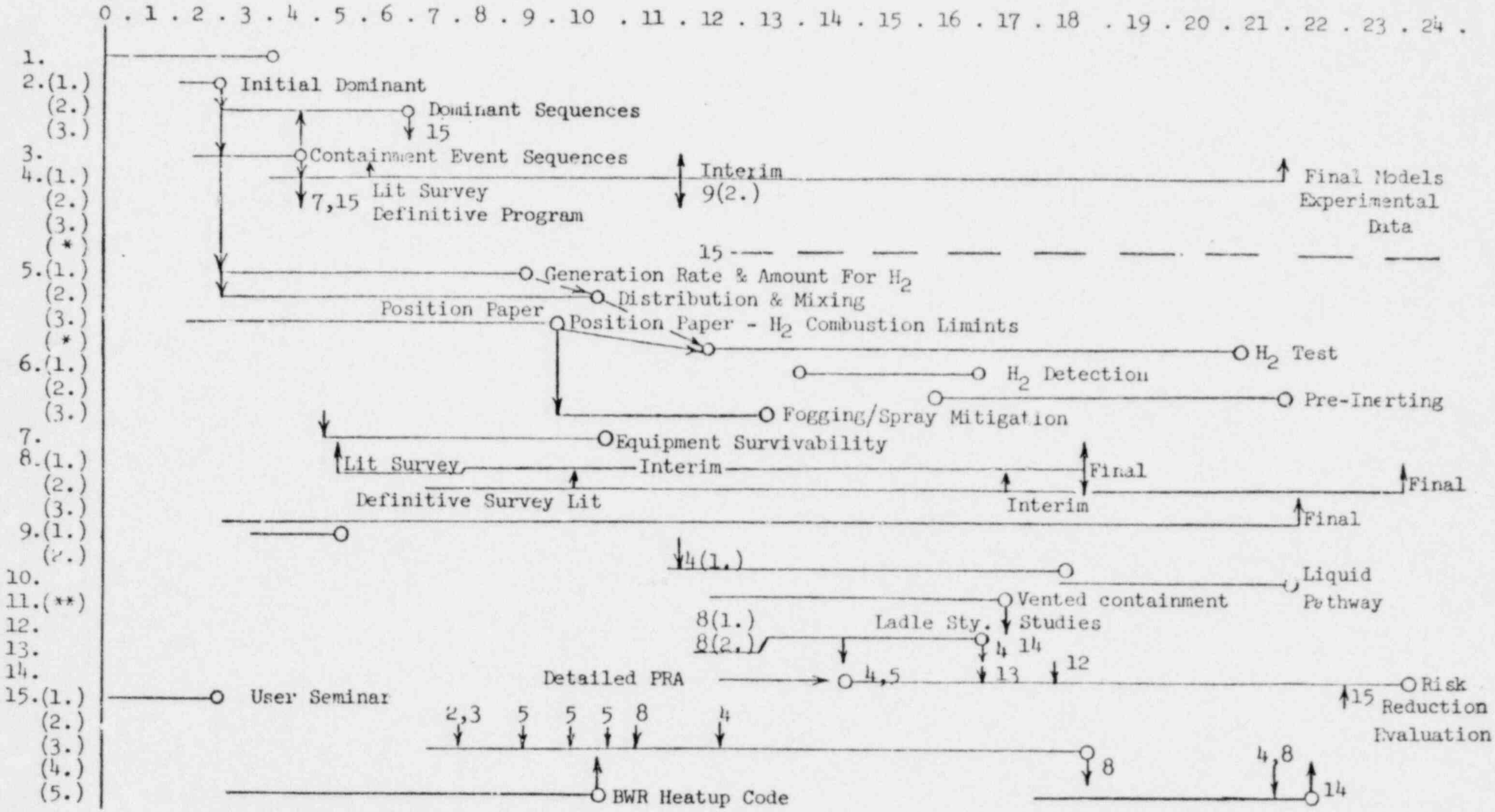
e. EPRI/NSAC TMI Code

Develop, qualify, and document the BWR damage progression equivalent code.

See Appendix A-1 for more information.

A.2 Schedule

The preliminary schedule for the 15 AIF tasks is shown in figure II.A-1.



* Identified Contingency

** Integrate with DOE/EPRI

PRELIMINARY PROJECT SCHEDULE

Figure II.A-1

A.3 STATUS

TVA is considering participation in the AIF program.

B. Electric Power Research Institute (EPRI)/TVA/Duke/AEP

B.1 Scope

EPRI has developed the following tasks and has received proposals from the listed organizations to accomplish each of the projects.

1. Development of preliminary testing of deliberate ignition systems (Rocketdyne Division of Rockwell);

2. Experiments and analyses on basic hydrogen combustion phenomena including the effects of steam, turbulence, and the potential for transition to detonation (AECL Whiteshell);

3. Experiments on hydrogen control methods including water spray, fog, and Halon (Acurex);

4. Measurement and analyses of hydrogen mixing and distribution with natural and forced convection (HEDL- W).

See Appendix A-2 for more information.

B.2 Schedule

The preliminary schedule for the four tasks is shown in figure II.B-1.

Proposed Schedule for EPRI Tasks

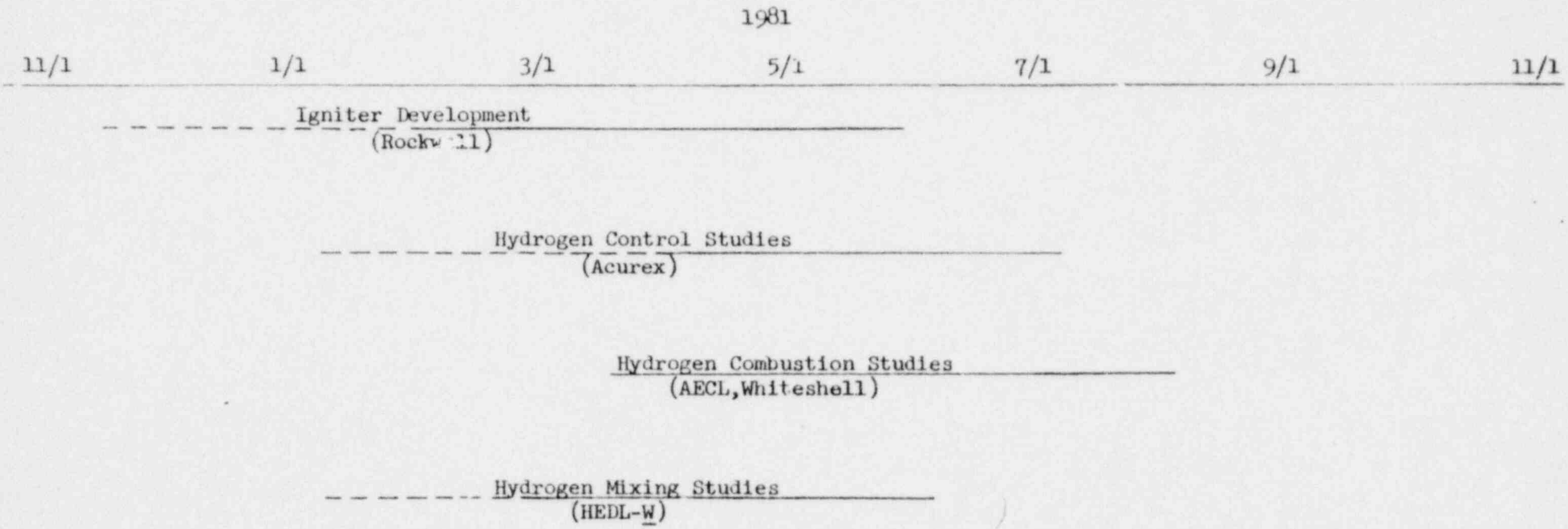


Figure II.B-1

B.3 Status

Details of the EPRI program are still being finalized. TVA, Duke, and AEP have agreed to participate fully in the funding and management of the EPRI program.

C. Westinghouse/TVA/Duke/AEP

TVA, Duke, and AEP are cooperating with Westinghouse in two major experimental and analytical efforts described in this section.

C.1 Fenwal, Incorporated

C.1.1 Scope

Westinghouse, under authorization from TVA, Duke, and AEP, subcontracted Fenwal, Incorporated, of Ashland, Massachusetts, to perform the phase 1 and 2 igniter testing program.

The purpose of the testing program was to:

Phase 1 - Determine if the igniter would burn hydrogen at concentrations of 8 to 12 percent for various environmental conditions of pressure, temperature, air flow across igniter, and humidity.

Demonstrate igniter durability.

Phase 2 - Establish the lowest hydrogen

concentration at which the igniter would initiate burning.

Determine the igniter's ability to function in a spray environment.

Measure the gross effects of a hydrogen burn on a representative sample of equipment.

Confirm multiple burns due to continuous addition of hydrogen.

Provide more empirical data for support of igniter licensing.

C.1.2 Schedule and Status

All Fenwal testing has been completed. A report by Fenwal, Incorporated, on Phase 1 testing and an evaluation report by TVA and Westinghouse on Phase 1 and 2 testing have been completed and were submitted to the NRC about December 1, 1980. (See Appendix N of Volume 2 of the TVA Sequoyah Nuclear Plant Degraded Core Program Report.) The Fenwal report on Phase 2 is due shortly.

C.2 CLASIX Modifications

C.2.1 Scope

TVA, Duke, and AEP have authorized Westinghouse/Offshore Power Systems to implement the following modifications in the CLASIX code:

Addition of structural heat sinks

Addition of structural heat transfer correlations

Addition of air return fan head/flow model

C.2.2 Schedule

These modifications will be completed during the first quarter of 1981.

C.2.3 Status

CLASIX with structural heat sinks currently being debugged.

Radiative heat transfer module under development.

Development of air return fan model pending receipt of information from fan manufacturer.

D. TVA/Duke/AEP

D.1 Halon (Atlantic Research Corporation)

D.1.1 Scope

TVA, Duke, and AEP have authorized Atlantic Research Corporation to perform the following tasks:

Preliminary Halon injection system design

Investigation to determine if combustion of inerted mixtures can be initiated within a blast wave

Determine amount of Halon that may decompose postaccident inside containment

Study the change in water chemistry due to Halon decomposition

Investigate additives to prevent Halon decomposition

D.1.2 Schedule

Interim report submitted - 11/15/80

Work of Atlantic Research Corporation to be finished - 12/15/80

Final report to be presented - 1/15/80

D.1.3 Status

Watts Bar Nuclear Plant visited by Atlantic Research Corporation personnel and their subcontractors.

Information concerning ice condenser containments sent to Atlantic Research Corporation to aid them in their study.

Information concerning containment materials sent to a subcontractor to Atlantic Research Corporation.

Interim report received by TVA/Duke/AEP (see Appendix A-3).

D.2 Electromagnetic Interference (EMI) Study

D.2.1 Scope

TVA, Duke, and AEP have authorized consultant Dr. Bernhard Keiser (Keiser Engineering, Vienna, Virginia) to perform the following tasks:

Assess the electromagnetic interference emissions from spark-type igniter for:

- Direction
- Frequency
- Intensity
- Effects on instrumentation

Design suppression or shielding equipment which is compatible with:

- Established seismic requirements
- Flow and combustion requirements (if suppression equipment is located around the igniter)

Test suppression or shielding equipment to verify design.

D.2.2 Schedule

Provide EMI consultant with one Flaregas Corporation igniter, Model Number ETX-105 - 12/1/80

Provide consultant a list of instrumentation located in containment, the manufacturer of this instrumentation, and a contact at the manufacturer for technical information - 12/1/80

Test igniter for emission profile - 12/8-9/80

Report on igniter testing - 1/20/81

Shielding/filtering preliminary design complete - 2/13/81

Onsite testing of shielding/filtering design complete - 3/3/81

Final report o' onsite testing complete - 3/20/81

D.2.3 Status

Consultant has received the list of instrumentation and a contact for each manufacturer involved from TVA.

Consultant has received the Flaregas igr'ter.

Testing of the igniter for emission profile to begin December 8, 1980.

D.3 Catalytic Combustor

D.3.1 Scope

TVA, Duke, and AEP are currently evaluating a proposal from Acurex Corporation to perform the following tasks:

Investigate catalyst flammability limits and heat release capabilities at:

- inlet gas temperatures below 250°F
- low hydrogen concentrations in the presence of poisons
- water concentrations from 5 to 80 percent

At each point, identify:

- catalyst light-off temperature
- pressure drop across catalyst
- combustion efficiency
- bed temperature profile

- maximum throughput

D.3.2 Schedule

The experimental work would take approximately two months.

The final report would be presented approximately one month after completion of the experimental work.

D.3.3 Status

The proposal from Acurex is currently being evaluated and defined by the utilities.

No contract has been approved.

D.4 Fogging

D.4.1 Scope

TVA, Duke, and AEP have agreed to participate in the funding and management of the EPRI program (see B above) which includes the following tasks which have been proposed by Acurex:

Effect of fog on lower flammability limit

Effect of fog on a deflagration

Effect of fog on the transition to detonation

Effect of deflagration on equipment with a fog present

TVA, Duke, and AEP are currently pursuing additional consultants to aid in the investigation of fogging as a hydrogen mitigation.

D.4.2 Schedule

Acurex preparation for experimental work will begin 1/1/81 and end 3/31/81.

Acurex experimental work will begin 4/1/81 and end 7/1/81.

D.4.3 Status

Acurex has located a test facility for use in this study.

Details of the EPRI program are still being finalized.

E. TVA

In addition to the preceding, TVA is independently pursuing other areas of degraded core studies which are outlined in this section.

E.1 Browns Ferry Nuclear Plant Probabilistic Risk Assessment (Pickard, Lowe, and Garrick)

E.1.1 Scope

In an effort to quantify the risk to public health and safety of the Browns Ferry Nuclear Plant, TVA has contracted the firm of Pickard, Lowe, and Garrick (PLG) to perform a risk assessment study of Browns Ferry Nuclear Plant unit 1.

Specific tasks to be accomplished in the study include:

- Identification of dominant event sequences leading to the Browns Ferry Nuclear Plant risk, including quantification of their probability of occurrence.

- Fault trees wil be developed to evaluate the contribution of component failure to the total system failure. Operator action and common cause failure will be included.

- Specific Browns Ferry Nuclear Plant site characteristics will be used to evaluate radiological consequences.

- A comparison of the Browns Ferry Nuclear Plant risk with other nuclear plant risk studies and acknowledged societal risks will be performed.

During the study, PLG is to train TVA personnel in the techniques of risk assessment.

E.1.2 Schedule

The study began 10/80

Dates for major milestones

- Data analysis, event trees, and fault trees - 3/81

- Explant consequence model assessment - 4/81

- Seismic analysis reports - 7/81

- Explant consequence analysis - 9/81

- Final report - 12/81

E.1.3 Status

Tasks completed or presently underway:

- Obtaining of plant specific maintenance and operating data

- Identification of preliminary event initiators

- Definition of event sequence diagrams

Near future tasks

- Accident sequence analysis

- System failure analysis

- Seismic analysis

E.2 Sequoyah Nuclear Plant Full-Scale Safety and Availability Analysis (Kaman Sciences Corporation)

E.2.1 Scope

The full-scale safety and availability analysis of Sequoyah Nuclear Plant being performed by Kaman Sciences Corporation (KSC) with EPRI funding and TVA cooperation has several objectives.

- Qualitative and quantitative safety, reliability, and availability estimates

- Sensitivity studies identifying components, equipment, procedures, and operator action with most significance to safety and availability

- Identification of system components in low order fault sets affecting safety and availability

E.2.2 Schedule

Phase I (preliminary assessment) 1/81

Phase II (final assessment) 1/82

E.2.3 Status

Comprehensive system models have been developed.

Preliminary top level models and a plant availability assessment have been drafted.

E.3 Consequence Analysis

E.3.1 Scope

Provide TVA capability to analyze phenomena associated with degraded core accidents

Evaluate key sequences for Sequoyah and other TVA plants

Multifaceted analysis encompasses

- Primary system thermal hydraulics (PT and core melt)
- Containment repsonse (PT, burning, and concrete interaction)
- Fission product transport (aerosol and plating)
- Evaluation of public risk

E.3.2 Schedule

Consecutive analysis code package (MARCH/CORRAL/others) - 12/80

Develop Sequoyah base case models - 1/81

Obtain consultant and conduct consequence assessment training - 2/81

Identify high priority accident scenarios - 2/81

Run MARCH analyses - 3/81

Input MARCH results to consequence codes - 4/81

Identify needed MARCH improvements - 4/81

Input TVA MARCH experiences to industry code improvement effort - 6/81

Assess analysis results for development/ verification of TVA permanent hydrogen control system - 3/81-7/81

E.3.3 Status

Latest MARCH version obtained (October 1980 and November 10 update)

CORRAL/CRAC obtained from SAI

Sequoyah base case model prepared, testing begun

S_2D, TMLB', and AD sequences selected for preliminary consequence assessment

Battelle, Columbus Laboratory, selected for degraded core analysis training program

E.4 Singleton Testing

E.4.1 Scope

TVA has continued to perform igniter reliability and endurance testing at its Singleton Lab.

Several General Motors 7G glow plugs were energized with voltages ranging from 11.0 volts ac to 14.0 volts ac, and the surface temperatures at the different voltages were noted

302 General Motors 7G glow plugs were subjected to a preconditioning test designed to eliminate plugs with manufacturing defects.

50 GM glow plugs were selected at random from the group of plugs which successfully passed the preconditioning test for additional cycling and endurance testing.

E.4.2 Schedule and Status

Endurance testing of the 50 GM glow plugs is continuing (see Appendix A-5 for further information).

Similar reliability and endurance testing of Bosch glow plugs will begin in the near future.

E.5 Severe Accident Sequence Analysis (SASA)/(ORNL)

E.5.1 Scope

The NRC is conducting a severe accident sequence analysis (SASA) program which involves four national laboratories. TVA is participating with Oak Ridge National Laboratory (ORNL) in its SASA studies involving Browns Ferry Nuclear Plant unit 1. The purpose is to improve best-estimate understanding of the phenomenological sequence of nuclear reactor accidents with partial or total core melt and to determine improved means for mitigating the accidents and containing the fission products. Program products include:

- Documented calculations of plant response to a broad spectrum of accident sequences including events beyond the design basis

- Graphical overviews of the progression of accident sequences as a function of time

- Analyses of operator information needs, alternative mitigating or aggravating actions, and consequences of those actions

- Delineation of accident management strategies

Program tasks include:

- Develop accident sequence charts with timing information to guide potential corrective action for a station blackout and a loss-of-heat-sink scenario

- Analyze system interactions

- Analyze factors leading to direct failure of containment

- Identify critical equipment and instrumentation and critical requirements for operator action

- Analyze fission product behavior and inherent retention phenomena

- Determine limits of coolability for varying fuel melt configurations

- Determine limits of containment capability for varying fuel melt configurations and varying degrees of malfunction

E.5.2 Schedule

- Develop time-line chart for station blackout case with potential corrective action - 12/80

- Integrate instrumentation modeling with overview model - 1/81

- Develop list of pertinent instrumentation, locations, function, and potential effects of station blackout accident sequence - 2/81

- Complete fission product transport calculations for station blackout sequence - 9/81

- Issue draft final report for station blackout sequence - 10/81

E.5.3 Status

- Time-line chart for unperturbed station blackout sequence has been developed.

- RELAP calculation has been performed for the core with no ac power and no ECCS function

- MARCH has been made operational, and a BFN model is being constructed

- An (incomplete) overview model (simulation) has been developed for comparison with more detailed analyses.

E.6 Ice Condenser Containment Code

E.6.1 Scope

- Develop a TVA in-house capability to analyze pressure and temperature transients for severe conditions in an ice condenser containment.

- Present ice condenser containment codes available:

  a. LOTIC - Westinghouse proprietary

  b. CONTEMPT-4-Developed by EG&G - not operational due to errors

- Possible strategies

  a. Modify existing containment or sub-compartment codes (CONTEMPT-LT, COMPARE, etc.)

  b. Write a new code

- Decision

  CONTEMPT-4 was chosen for the basis of the TVA code because it offered:

a. State-of-the-art features such as dynamic storage allocation

b. Multicompartment model

c. Ice condenser

d. Basic containment features available; e.g., sprays, heat sinks, fans, and heat exchangers

e. Potential for rapid development

E.6.2 Schedule

The code development program consists of three parts:

Part I

Obtain a working code that will analyze conventional containment transients (LOCA, MSLB) - 1/15/81.

Part II

Expand and modify the code to allow evaluation of Class 9 events - 4/1/81

a. Add a hydrogen burn model

b. Consider multicomponent atmosphere (H_2, N_2, O_2, CO_2, H_2O, etc.)

c. Model radiative heat transfer from atmosphere to heat sinks

d. Extend range of code to permit high temperatures

Part III

Continuing development of a best estimate code - ongoing beginning 4/1/81

a. Develop a dynamic ice condenser model

b. Improve abilities to track H_2 concentrations

E.6.3 Status

Part I - approximately 50-percent complete

Part II - approximately 10-percent complete

Part III - currently in planning

APPENDIX A-1
AIF PROGRAM - TECHNICAL DETAILS

INITIAL PROGRAM PLAN

This initial program plan identifies he integrated efforts believed necessary to generate sufficient technical infor ation to develop rational positions on key degraded core issues and to provide the base for successful degraded core rulemaking hearings.

The program has been scoped to incorporate the results of known programs--industry, NRC, foreign--and includes only those efforts necessary prior to participation in the rulemaking.

Based on current knowledge, it is unlikely that any simple solutions are available; there are gaps in the technological information which must be filled to develop and defend rational positions, and there is a nee for effective understanding of the complete picture regarding degraded co issues and strong management of an integrated program.

The program is focused on obtaining sufficient information, not defeloping information for the sake of information.

The program is defined in related segments. These segments have been derived from an overview of the degraded core situation as follows.

The industry will develop rational positions related to the characterization of residual risk from degraded core conditions and the potential alternatives for further prevention or mitigation of residual risk.

A safety goal or criteria that provides a measure of acceptability is a necessary condition for effective evaluation of residual risk.

The release of radioactivity to the environment is cause of deleterious consequences. Releases can occur only if both large quantities of radioactivity are produced and released from the primary system and the containment is ineffective.

The release of radioactivity to the environment is the cause of delete deleterious consequences. Releases can occur only if both large quantities of radioactivity are produced and released from the primary system and the containment is ineffective. The attenuation prior to containment failure must also be considered.

Even if releases to the environment are postulated, significant attenuation mechanisms are physically real and act to reduce the consequences.

Residual risk evaluation must include both the probability of occurrence and the consequences. Reducing either the former through prevention or the latter through mitigation is a viable means of risk reduction.

Based on these general precepts, the program structure develops and interrelates as described below.

Define the role of the specified safety criteria.

Identify the dominant sequences of events contributing to risk--dominant means those where the combination of probability of occurrence and predicted consequences of the sequence is significant in the risk.

Identify the core degradation and containment transient phenomena which are critical to determining the challenge to the containment or the quantity and timing of release of activity.

For critical phenomana, develop sufficient information to adopt rational positions on the magnitude and effects on containment or release. Based on previous studies and experience, the critical phenomena include the generation and burning of hydrogen, steam generation resulting from core debris-water interaction, core debris coolability including consideration of core debris-concrete interaction, and radioactive product transit and deposition.

Perform integrated analyses of the spectrum of dominant sequences with appropriate ranges for the critical phenomena to determine the margin currently existing for toleration of degraded core events.

Identify the advantages and disadvantages of alternative preventive or mitigative measures including concepts actively being pursued by NRC.

Quantify the risk reductions achieved and the relative risk reductions achieved if alternative preventive or mitigative measures are considered.

The separate tasks are:

1. Safety Goal/Criteria Application
2. Selection of Dominant Sequences
3. Identification of Phenomenological and Containment Transient Critical Sequences
4. Steam Overpressure Phenomena (In-Vessel, Containment)
5. Hydrogen Generation and Burn
6. Hydrogen Burn Control
7. Equipment Survivability for the Degraded Core Environ ent
8. Core Debris Coolability
9. Containment Structural Capability
10. Evaluation of Liquid Pathway Dose
11. Fission Product Liberation and Removal
12. Vented Containment Systems .
13. Core Ladle
14. Residual Risk Reduction Evaluation
15. Integrated Model Definition and Analysis

For each task, the following sheets identify the relationship of the task to overall jectives, the information known to be available, the scope of the recommenaed actions, the schedule and budgetary estimates.

1. SAFETY GOAL/CRITERIAL APPLICATION

Relationsnip to Objectives: A safety goal/criteria is a necessary condition for proceeding with the rulemaking. There must be:

a. Acceptability limits for individual and population health effects including both probability and consequences,
b. Risk/benefit criteria for alternative evaluation
c. Definition of methods for evaluation of degraded core conditions (realistic analysis of transients, no arbitrarily postulated equipment failures, use of realistic ultimate containment pressure capability, etc.)

Without these items, there is no common basis for decisions regarding acceptability of current designs, the relative benefits of alternative features, and the analytical results obtained for containment transients.

Available Information: For the proposed program, it has been assumed that the development of the safety criteria has been successfully completed through current industry efforts. Since the current AIF goal proposal is consistent with the needs, this assumption seems warranted.

With respect to methods for evaluation, information is available from on-going work in the following studies: Zion-Indian Point, TVA/Duke/AEP, Limerick, and NRC companion studies. However, a comprehensive written position is not currently available.

Scope of Recommended Actions:

a. Generate position paper on the role of safety goal/criteria in the degraded core rulemaking activities

b. Generate comprehensive criteria for methods for evaluation of degraded core conditions

Schedule/Budget: It is estimated that 2MM of effort will be required to generate the position paper and comprehensive criteria. These must be completed prior to initiation of major analytical or design alternative evaluation efforts.

Significant broad based review of the criteria and position paper are required, and the effort necessary is assumed contributory on the part of the involved and interested parties.

2. SELECTION OF DOMINANT SEQUENCES

Relationship to Objectives: Understanding the sequences of failures necessary to cause a degraded core condition is fundamental to analyzing the resultant containment challenges of evaluating preventive or mitigative features. This understanding must include the mechanisms (equipment failures, operator interactions, etc) and the relative probabilities and consequences of the sequences.

The dominant sequences are those which contribute measurably to the risk, i.e., those sequences whose combined probability and consequences are relatively higher than the remainder. By selecting the dominant sequences, the analytical and evaluation efforts are focused on areas where significant gains can be achieved.

Available Information: For defining dominant accident sequences, a considerable technical base is available from similar studies, either complete or due to be completed in the near term. These include: the Reactor Safety Study (WASH-1400), the NRC Reactor Safety Study Methodology Application Program (RSSMAP) which includes studies on four additional reactors, the individual plant studies including Zion-Indian Point Mini-WASH 1400 and complete study, TVA Sequoyah studies, the NSAC/Duke Oconee study, the Philadelphia Electric Limerick study, and others.

In addition, studies on Auxiliary Feedwater Reliability, the IREP Program, and Inadequate Core Cooling studies each provide additional information useful in defining dominant accident sequences.

For the early phases of this program, the assimilation and integration of this available information is necessary. Although the information is useful, direct application without informed scrutiny would not provide the proper base for proceeding of particular importance is the inclusion of operating plant experience in defining the dominant sequences.

In the later phases of this program, integrating the results of major on-going studies is necessary, since no resource is provided in the program for performing studies to this level of detailed information.

Scope of Recommended Actions: The scope of this task is to define the dominant sequences and rational for selection and provide documentation. This scope is divided into three parts:

(1.) Initial definition of "likely" dominant sequences based on available material, an initial ranking of sequences in terms of probability and consequences and a definition of currently available preventive and mitigative (e.g., containment heat removal) systems would be prepared.

This effort would be performed by small groups of individuals highly familiar with the plant systems and operations supported by personnel thoroughly familiar with the application of Probabilistic Risk Assessment techniques.

This task would be performed at the outset of the program (approximately one month duration) by a group of utility engineering/operating, NSSS vendor, AE and PRA personnel. Following assingment to the team and a material review period, one meeting of each team would be convened to establish the initial likely dominant sequences. Based on 2 MW per individual, 8 individuals for BWR, 6 indivuals per PWR NSSS vendor type, the total estimate is 13 MM, 4 CRU.

To maximize productivity, it is assumed that the necessary picked personnel are made available and that the PRA personnel on each team are the same as assigned to "(2.)" below.

(2.) Dominant Accident Sequence Assessment, Quantification and Documentation: The objective is to quantify the dominant sequences defined in "(1.)" identify any other sequences that should be considered, provide preliminary consequence assessments, and document the process and rationale for selection of dominant sequences.

Input to this task includes the output of the task "(1.)" above and the preliminary containment sequence identification task.

The output is a document identifying how and why the dominant accident sequences were chosen and integrating the results of previous studies into the industry position. Identification of similarities and differences between the final result and other studies is important.

This task is estimated to require 6 MM for all BWR types and 4 MM for each PWR type over a 4-month period with 6 CRU. It is assumed that this task will be performed by personnel highly qualified in Probabilistic Risk Assessment techniques who participated in task "(1.)" above.

(3.) Update to include detailed study results: After detailed studies (Zion-Indian Point, NSAC/Duke, Limerick, TVA, etc.) are completed, these results would be integrated into the dominant accident sequence selection and rationale. The detailed studies should provide the in-depth technical basis for the dominant accident sequence selection.

This task is estimated to require 6 MM of effort assuming personnel familiar with the detailed studies are available.

Schedule/Budget: Given above.

3. SELECTION OF CONTAINMENT PHENOMENOLOGICAL SEQUENCES

Relationship to Objectives: Identification and understanding of the critical phenomena of degraded core conditions which lead to containment challenges is necessary to evaluate the inherent plant margins and the effects of proposed mitigating features. The identification of the containment sequences in conjunction with the dominant accident sequences focuses the analytical and experimental efforts on the critical areas related to system or containment failure challenges. A comprehensive identification of containment sequences assures that analyses or features are considered only if broadly significant.

Available Information: The Reactor Safety Study (WASH-1400), NRC studies on mitigating features, and on-going industry studies (Zion-Indian Point, Limerick, TVA/Duke/AEP) each provide information on core degradation phenomena and the importance with respect to containment challenge.

Further information in specific areas (hydrogen generation and burn, core degradation progression, etc.) is identified in tasks below.

Scope of Recommended Effort: The scope of this activity is to generate containment phenomenological event trees (or equivalent) for the major reactor systems. The containment event tree (or equivalent) would start where the dominant accident sequence effort terminates, i.e., conditions for core degradation have been postulated to occur. The event tree would identify the significant branch points thereafter until recovery or containment failure (with associated releases) terminate the progression. The significant branch points (nodes) would be chosen based on knowledge gained from current studies on the phenomena which could lead to containment challenge, e.g., hydrogen release and burn prior to core melt, steam pressure generation from core debris-water interaction. By properly defining the nodal decision points, the event tree (or equivalent) can be used to determine the best estimate progression paths as well as less likely paths, eliminate physically unrelizable paths, provide a framework for relative probabilistic evaluations of progressions, and focus the analytical and experimental efforts. The dominant sequence efforts coupled with the containment event tree (or equivalent) provide the framework for evaluating the residual risk reduction of proposed mitigating alternates.

The intent is to generate a minimum number of containment phenomenological event trees which provide comprehensive generic coverage of the core degradation and containment transient phenomena for light water reactors. For this estimate, it has been assumed that two (one for PWR and one for BWR are necessary).

The effort is in two phases: The first to establish the event tree logic, and the second to provide integration of the phenomenological developments of subsequent tasks and estimated ranges of probabilities for the nodes.

Budget/Schedule: Based on the availability of current work and using personnel thoroughly familiar with the plant types and phenomenology, the development on the initial containment event trees (or equivalent) is estimated to require 4 MM for each (BWR and PWR). This effort requires input from the initial selection of dominant accidents and provides fundamental guidance for the remaining major activities.

Given the event tree structure, analytical and phenomenological efforts, integration and estimates of probability ranges would require 3 MM late in the program.

4. STEAM OVERPRESSURE PHENOMENA (IN-VESSEL, CONTAINMENT)

Relationship to Objective: Production of large energies or quantities of steam from the interaction of core debris with water is one of the major postulated mechanisms for causing containment failure. Since a wide range of steam production rates can be calculated depending on the assumptions used in the analysis, it is necessary to develop technically based positions on the phenomena involved and the uncertainties in the theoretical and experimental bases for these phenomena. For realistic evaluations of residual risk, bounding calculations on the production of steaming are misleading at best. The proper approach is to evaluate the phenomena realistically based on current knowledge, specifically identify uncertainties, and provide an integrated assessment of the potential for containment challenge resulting from core-debris-water interaction.

Since the amount of debris, rate of interaction, and initial conditions of debris-water-system complex, are all interrelated, this phenomenological evaluation includes the determination of appropriate models for core degradation melt progression, (included in task 8) necessary conditions for steam explosion initiation, dynamics of mixing and steam generation between core debris and water, and conditions for missile generation and analyses of results of missiles.

Available Information: The Reactor Safety Study (WASH 1400), NRC studies related to mitigating features, vapor explosion research in the metals and LMFBR areas, and Zion-Indian Point/Limerick industry studies all include information relating to these phenomena.

Extensive research programs in these areas have been or are being carried out at Sandia, Argonne, Hedl, Brookhaven, Battelle-Columbus, Purdue University, and German facilities, as well as various other sites.

Scope of Recommended Actions: The overall scope of the activities listed below is to provide sound phenomenological models for the progression of core melt for the identified dominant sequences, the conditions necessary for occurrence of steam explosions and effects of resultant explosions based on proper conversion efficiencies, mixing dynamics of core debris-water interactions, steam generation rates for core debris-water interactions, and the dynamic effects of large scale core debris-water interactions on the materials involved given typical reactor plant geometries. The task is divided into parts. For each part, the intent is to develop the following information:

a. Description of phenomena involved
b. Relationship of phenomena to containment challenge
c. Description of the physics underlying the phenomena
d. Available theoretical models and experimental evidence
e. Best estimate progression path
f. Range of uncertainties that should be considered
g. Recommended model(s) for analysis
h. Recommended experimental efforts

(1.) Steam Pressure Generation and Steam Explosion
The task includes providing the above information for the interaction of large quantities of core debris (molten) with water in several possible configurations: Core debris poured into water with and without elevated pressure conditions initially, and water poured onto core debris. The necessary and sufficient conditions for occurrence of steam explosion would be identified. The appropriate range of thermal to mechanical energy conversion associated with physically relizable steam explosions would be defined.

For steam pressure generation, mechanistic models for the rate of heat transfer and the amount of heat transfer would be developed. Where hydrodynamic effects are likely to be significant, the models should provide for inclusion. Particle size effects hould be included based on the information developed below in (2.)

(2.) Dynamics of Mixing and Steam Generation
This task includes providing the above information for the dynamics of mixing large quantities of core debris and water. The physical requirements that must be met for coherent, rapid mixing would be

established. Included would be the potential effects of the energy required for mixing and mechanisms for supplying the energy, local thermal interactions, hydrodynamic dispersion effects, particularization of the debris, crust formation among others. Based on the information developed, mechanistic models for steam generation would be developed.

Depending on the results of this effort and the assumed pursuit of the current NSAC and planned EPRI program with ANL, experimental work broadening the technical base may be desirable. This could include: varying core debris injection mode, varying initial pressure conditions, and simulant material tests to establish specific mechanisms. This effort should presently be considered contingency.

(3.) Structural Response of Equipment

Based on the results of (1.), this task would establish the conditions for missiles or ex-vessel steam explosion phenomena. Establishing the necessary conditions for missile generation for physically realizable steam explosions includes identification of the means for rapid momentum transfer to the structure. Based on analyses to date, it is likely that such transfer is improbable at best. Ex-vessel steam explosion phenomena and resultant structural loadings will be assessed.

It is assumed that the current study results provide a reasonable assessment and that extensive structural analyses will not be required.

Budget/Schedule: For each task above, the following sequence would apply--

a. Literature survey and precise definition of program and results (1-3 months after initiation)

b. Interim Report covering Items A-E in detail (6-9 months after initiation)

c. Final Report including models and experimental data (12-18 months after initiation)

The estimated resources to complete the tasks are:

(1.) Steam Pressure Generation and Steam Explosion Phenomena -
18 MM plus 40K

(2.) Dynamics of Mixing and Steam Generation -
24 MM plus 75K
(30 MM plus 100K additional to EPRI-ANL contingency--performed after decision based on Interim Report)

(3.) Structural Response of Equipment
10 MM plus 20 CRU

5. HYDROGEN GENERATION AND BURN

Relationship to Objectives: The results of ignition of large quantities of hydrogen represents one significant postulated mechanism for causing containment failure. A wide range of postulated hydrogen production rates and amounts, hydrogen distributions, and hydrogen ignition phenomena can be calculated or used in calculations of containment transient pressure loadings. Development of technical bases for each of these areas including uncertainties is necessary to the generation of intelligent positions on the potential for containment challenge from these phenomena. The proper approach is to evaluate the phenomena realistically based on current knowledge, specifically identify uncertainties, and provide an integrated assessment not to do bounding or physically unrealistic calculations.

Available Information: Considerable literature exists related to the combustion of hydrogen. Compendiums of this literature have been prepared by Sandia and EPRI/NSAC. In addition, significant analytical and experimental work has been performed outside of the U.S. (e.g., Battelle - Frankfurt, Germany.)

EPRI/NSAC and the Department of Energy are actively initiating or pursuing programs; analytical and experimental coordination with these is mandatory.

Work completed or in progress in the Zion-Indian Point, Limerick and TVA/AEP efforts is directly applicable.

Scope of Recommended Actions: The scope of this task is to provide sound phenomenological models for the generation, distribution, ignition and combustion of hydrogen as related to LWR conditions. The task is divided into parts. For each part, the intent is to develop the following information:

a. Description of phenomena involved
b. Relationship of phenomena to containment challenge
c. Description of the physics underlying the phenomena
d. Available theoretical models and experimental evidence
e. Best estimate progression path
f. Range of uncertainties that should be considered
g. Recommended model(s) for analysis
h. Recommended experimental efforts

(1.) Generation Rate and Amount of Hydrogen

For the dominant accident sequences, determine the rate and amount of zirconium-water or stainless-steel-water reaction producing hydrogen for both intact core geometry and core debris-water interaction progressions. Currently available experimental data and models whould be used and improved to determine the best estimates of hydrogen production rates and amounts and to identify the appropriate ranges of uncertainties.

(2.) Hydrogen Distribution

This part includes two areas: a position paper compiling previous work on the large scale mixing characterisitcs of hydrogen and the conditions necessary to prevent significant stratification or pocketing, and system (or small scale) analysis of distribution and mixing of hydrogen.

For the second area, determine analytically the potential distributions assuming hydrogen rich releases (characteristic of the dominant accident sequences) into air atmospheres for conditions characteristic of releases into containment volumes, through suppression pools, or though ice condensers of spray curtains. Included in these analyses are the effects of turbulence, geometry, heat transfer and condensation as important to determining the hydrogen concentrations. Define the need for and boundary conditions for localized turbulent deflagration or detonation analyses. Based on material available, develop the necessary models for anlayses of these phenomena.

(3.) Combustion Limits of H_2-Air-Steam

This part includes the compilation of available material and development of models for burning of hydrogen in conditions representative of the dominant accident sequences as developed in the containment event sequence. Included are the definition and characterization of the flammability limits (upward propagation, upward-wideward-downward propagation, transition from deflagration to detonation, turbulent deflagration, detonation), effects of diluents including steam, temperature and pressure effects on flammability limits, scale and geometry effects, and water spray/fogging effects. Definition of pressure developed, burn velocity and flame front propagation velocity models would be included.

The EPRI (or EPRI/DOE) program has been assumed to continue and to provide information--particularly large scale experiments.

The EPRI/NSAC/ANL program on hydrogen blanketing of the zirconium-water reaction would be a worthwhile, but not necessary addition as of today with respect of H_2 generation rates.

Budget/Schedule: For each of the above, the following sequence would apply -

a. Literature survey and precise definition of program and expected results (1-3 months after initiation)
b. Interim Report covering Items A-E in detail (6-9 months after initiation)
c. Final Report including models and experimental data (12-18 months after initiation)

The estimated resources to complete the tasks are:

(1.) Generation Rate and Amount of Hydrogen
15 MM

(2.) Hydrogen Distribution
30 MM

(3.) Combustion Limits of H_2-Air-Steam
8 MM

For budgetary purposes, a contingency of 200K for experimental work in this area should be included.

6. HYDROGEN BURN CONTROL

Relationship to Objective: Since the burning of hydrogen provides a potential challenge to the containment, means to prevent or control this burning must be defined and evaluated. The evaluation of these means would include feasibility, potential advantages and disadvantages particularly focused to evaluation of the benefits (negative, neutral or positive) with respect to risk reduction, and the impacts of including the alternative devices.

Available Information: The Sandia and NSAC hydrogen compendiums provide a general source for information. The on-going efforts, particularly TVA, provide a substantial further source of information with respect to pre-inerting; significant industry effort has been expended and data is available.

It has been assumed that present activities being carried out by TVA/Duke on ignitors and Halon injection will be completed and will form the basis for development of sound industry positions related to the evaluation of these means for prevention or mitigation of burn.

Scope of Recommended Activities: There are three areas in this task: survey of hydrogen detectors, evaluation of pre-inerting for containments not already evaluated, and evaluation of fogging/spray suppression.

(1.) Survey of Hydrogen Detectors

Establish the capabilities of currently existing equipment for detection of hydrogen including sensitivity, response time, environmental capabilities, etc. and document.

(2.) Evaluation of Pre-Inerting

For a representative gorup of containments, define the benefits and hazards of pre-inerting based on the containment accident transients developed below. The primary focus of this task is to define the impacts on availability, maintenance, personnel hazards and operations of pre-inerting.

(3.) Fogging/Spray Suppression

Define the necessary conditions for suppression or mitigation of large hydrogen burns through use of water spray or fogging systems. Define the advantages and disadvantages for this type of mitigation.

Budget/Schedule: The budget for these activities is identified as:

a. Survey of Hydrogen Detectors
   3 MM

b. Evaluation of Pre-Inerting
   12 MM (assuming 3 major type evaluations)

c. Fogging Spray Suppression
   3 MM

These activities do not need to be started immediately.

7. EQUIPMENT SURVIVABILITY FOR ENVIRONMENT (DEGRADED CORE)

Relationship to Objective: In the definition and analysis of degraded core sequences, certain equipment is assumed to remain operational, and other equipment is assumed not to fall into an intolerable state. It is necessary to define what minimum equipment must exist to permit termination or to monitor the status of the plant. The environment in which this equipment must operate must be defined and the capability of the equipment to survive must be developed.

Available Information: Information currently exists on the definition of necessary parameters as part of the TMI-actions. Information on environments either exists through on-going studies or will be developed as part of this industry program.

Scope of Recommended Activities: For five plant configurations (BWR, each NSSS vendor PWR, and ice condensor), the following tasks are recommended:

a. Identify the minimum set of functions which must be performed or equipment which must not operate as a consequence of the environment to permit termination of core degradation sequences or to monitor the status of the plant and return containment.

b. Based on "a.", identify necessary minimum set of generic equipment
c. Identify environments associated with the dominant sequences
d. Evaluate the survivability of the equipment in "b." for the conditions in "c." and define tests if necessary.
e. Develop recommendations on equipment survivability criteria and document results of complete task.

Budget/Schedule: The budget for this effort is estimated to be 4 3/4 MM per type, or 24 MM total.

For testing 100K should be included in contingency.

This effort should start after the containment sequences are defined.

8. CORE COOLABILITY

Relationship to Objective: The progression of a postulated core melt is the dominant factor in determining the potential for containment challenge. The amount of the core involved coherently (on a relatively short time scale) will effect the generation of steam pressures, the release of hydrogen, the vessel failure modes, the distribution of material subsequent to vessel failure, the ultimate coolability of the molten material, and the containment transients. Since the data base is currently limited to analytical/theoretical models and small scale experiments, the range of calculated transients can be extremely broad. It is necessary to develop sound phenomenological models based on current understanding and data, specifically identify ranges of uncertainties, and provide integrated physically consistent assessements of the potential containment challenges.

This phenomenological evaluation includes the progression of core melt prior, and subsequent to attaining melt temperature through loss of core geometry, slumping into the lower internals/bottom head, penetration of the reactor vessel, and ultimate disposition. Further, the conditions for termination of core degradation or melt progression would be developed. Finally, the conditions for coolability of the debris, including considerations of debris-concrete reactions, would be defined. By using the containment event sequences, an integrated assessment of the potential paths and termination points would be provided and sound technical information developed to support the case.

Available Information: The Reactor Safety Study (WASH 1400), NRC studies, Zion-Indian Point Study, Limerick Study, LMFBR data and foreign work all provide fundamental data for this effort. Further, industry TMI-2 damage progression analyses and evaluations provide significant input.

Scope of Recommended Activities: The overall scope of this effort is to provide technically sound, phenomenological models for the progression of postulated core melt for the dominant containment sequence events. The task is divided into areas. For each, the intent is to develop the following information:

a. Description of phenomena involved
b. Relationship of phenomena to containment challenge
c. Description of the physics underlying the phenomena
d. Available theoretical models and experimental evidence
e. Best estimate progression path
f. Range of uncertainties that should be considered
g. Recommended model(s) for analysis
h. Recommended experimental efforts

(1.) Analysis of In-Vessel Core Melt Progression and Recoolability

For each of the dominant accident sequences, determine the progression of the event from boiloff through major geometry disruption to penetration of the debris through the core supporting structure. The progression models should account for proper transfer of the heat of zirconium-steam reaction into the fuel, interassembly radiation, fuel relocation thermal propagators, melting/refreezing, quenching and particularization, and power profiles.

(2.) In-Vessel Coolability, Vessel Penetration, Ex-Vessel Coolability

The scope of this effort is to establish the limits for in-vessel coolability of debris, the modes and timing of vessel penetration, and the limits for ex-vessel coolability. The models developed would account for debris bed quenching, heat transfer between core debris and structures, structural failure predictions, conditions for and impact of crust formation, particularization of debris, limits for coolability of debris beds including power density--height--particle size--porosity considerations--and other effects which would substantially increase or decrease the debris coolability.

(3.) Core Debris Concrete Reaction

The scope of this effort includes the critical evaluation of currently existing models, development of rate of concrete penetration and non-condensible gas generation by refining current model estimates, and assimilating and following Sandia and foreign work in this area.

Budget/Schedule: For each task above, the following sequence would apply--

a. Literature survey and precise definition of program and results (2-3 months after initiation)

b. Interim Report covering Items A-E in detail (9-15 months after initiation)

c. Final Report including models and experimental data (15-24 months after initiation)

The estimated resources to complete the task are:

a. Analysis of In-Vessel Core Melt and Recoolability

50 MM 100 CRU

b. In-Vessel Coolability, Vessel Penetration, Ex-Vessel Coolability

60 MM 50 CRU 100K Experimental

c. Core Debris Concrete Reaction

18 MM

9. CONTAINMENT STRUCTURAL CAPABILITY

Relationship to Objectives: The structural capability of containment is the most significant mitigating feature identified to date. If the containment can withstand the pressure and temperature loadings imposed by the Postulated Core Degradation Events, there is no significant risk Establishing a uniform realistic base for determining the ultimate containment capability is essential to the completion of the effort.

Available Information: NRC and industry studies are available for Zion-Indian Point, Duke, TVA, Limerick and other plants.

Recommended Scope of Activities: The scope of this activity is in two parts: defining and integrating what has already been completed and identifying any residual issues; and two, defining and implementing a program for evaluating inertial (detonation or turbulent deflagration) loads or containments.

(1.) The first activity is to schedule a seminar of utilities and associated consultants who have performed realistic analyses of containment capability to identify what has been done, what residual work may remain, and what criteria should be proposed by the industry for these evaluations. These results would be documented.

(2.) The second activity is to define the inertial loadings which may be encountered (from Tasks 6 and 15) and specify the program of analysis of containment inertial load capability for performance. Strong consideration should be given to enlisting personnel experienced in weapons program analyses for consultation if not performance of this effort.

Budget/Schedule:

a. 2 MM to provide documentation assuming utility contribution of personnel to seminar

b. 2 MM to define loadings; 20 MM to perform analysis

The seminar should be scheduled early in the program. The inertial loading activity would be initiated following better definition of initial conditions from Task 6 above.

10. EVALUATION OF LIQUID PATHWAY DOSE

Relationship to Objective: The potential for increased risk due to transport of fission products through liquid pathways and the needs for interdiction of these was raised by the NRC. Generally, studies have shown that this is not a major risk contributor.

Available Information: NRC Liquid Pathways Study, Sandia Study, W Offshore Power Systems Liquid Pathways Study, and Battelle work all provide information.

In addition, work at Hanford on leading and transport may be available.

Recommended Scope of Activities: If this issue is raised, integrate available information and provide scoping information on the feasibility time span and cost of source interdiction.

Budget/Schedule: This work should not be initiated immediately, and in fact may not be necessary.

The effort for the above scope is 3 MM.

11. FISSION PRODUCT LIBERATION AND REMOVAL

Relationship to Objective: Even if containment failure is postulated, the amount of material liberated and the depletion of this material prior to reaching population is critical to determining the risk. Evidence exists that the current partioning and depletion is overly pessimistic.

Available Information: EPRI and DOE are pursuing the development of a program to improve the models currently used.

Recommended Scope of Activities: Immediately after initiation of the industry program, contacts with DOE should be made to determine the scope and schedule of the program being impelmented. The intent is to integrate the results of that program into the development of the industry positions on degraded core. Since it is likely that the DOE program will cover all necessary activities and that schedules could be adopted to fit the needs of this program, no effort separate from that program is presently estimated.

12. VENTED CONTAINMENT SYSTEMS

Relationship to Objectives: One mitigating feature currently being actively pursued by the NRC is the concept of venting the containment to prevent failure. It is necessary to identify the advantages and disadvantages, real contributions to risk reduction (positive, negative, neutral) and impacts of addition of this feature.

Available Information: NRC Studies (Sandia), D. Okrent work, Zion-Indian Point and TVA studies all include information relevant to this evaluation.

Recommended Scope of Activities: The scope of the task is to define the range of applicability of vented containment systems and maintain awareness of alternative pressure reduction systems.

a. Range of Applicability

Define the probability of need and types of events for BWR plants for which a venting system is a credible mitigating system. Define the gross requirements for a system in terms of sizing.

Establish the major design parameters and system design (without developing fine detail on design--sizes of filter beds are not required). Define the operational aspects of the system with particular attention to alternative valve/control arrangements for containment penetration. Evaluation of the benefits and hazards including probability of successful and spurious operations. Define in conjunction with Task 14 below the risk benefits (or lack thereof).

Budget/Schedule: This activity should be initiated later in the program unless NRC activities dictate that useful results would accrue by earlier performance.

The estimated resource for this is 20 MM.

13. CORE LADLE

Relationship to Objective: One mitigating feature currently being pursued by NRC is the core ladle. It is necessary to identify the advantages and disadvantages, real contributions to risk reduction (positive, negative, neutral) and impacts of addition of this feature.

Available Information: NRC/Sandia Studies and industry efforts (Zion-Indian Point, Floating Nuclear Platform) plus significant National Lab and foreign studies all include material related to core ladle design requirements, etc.

Recommended Scope of Activities: An evaluation of the real impacts of retrofitting combined with assessments in conjunction with Item 8 that cooling inherently provided by water loss is more effective is recommended.

Budget/Schedule: This effort should not be initiated immediately unless NRC activities provide another rationale for doing work early.

The estimated resource for this activity is 3 MM.

14. RISK REDUCTIONS ACHIEVED

Relationship to Objective: There are two purposes: First, highlight that actions taken and planned have reduced the likelihood of core degradation; and second, perform risk evaluations of the benefits if any, of alternative features either singularly or in combination.

Available Information: On-going PRA and industry degraded core studies and NRC studies should provide basic information for this effort.

Recommended Scope of Activities: Provide the capability to baseline a limited number (2-4) of plants using detailed PRA studies (e.g., Zion-Indian Point, NSAC/Duke, Limerick) and do risk tradeoff evaluations of alternative preventive or mitigative features and risk sensitivities of key phenomenological issues (e.g., H_2 burn, steam pressure). The assessments must include consideration in detail of new risks associated with additional features.

Budget/Schedule: Performance of the task requires baseline PRA and input information related to benefits/disadvantages of alternative features or phenomena from other tasks. It is estimated that the task could be performed in 6 months, and that 14 MM of effort would be required.

15. MODEL DEFINITION AND ANALYSIS

Relationship to Objective: An integrated analysis of the transients for degraded core considerations incorporating the results of the phenomenological model definition tasks is necessary. This analysis provides the capability to compare the results of the postulated events against the containment capability.

Available Information: Results from on-going studies (NRC and industry) and models (MARCH/CORRAL, EPRI/NSAC TMI Heatup Code, etc.) provide the basis for this effort.

Recommended Scope of Activities: The scope of this task is to provide the integrated analyses of the dominant sequences for representative plants and integrate the models developed in the previous tasks into this integrated analysis. There are five tasks defined below.

It has been assumed that the approach will be the modification of the MARCH /CORRAL system augmented by the EPRI/NSAC TMI Heatup Code. This assumption results from the facts that MARCH/CORRAL is immediately and widely available, provides capability for effective sensitivity analyses if properly "calibrated", and will be used by NRC and must therefore be understood in detail by industry.

(1.) Define MARCH/CORRAL Use

Convene personnel experienced with MARCH/CORRAL application and degraded core analyses to the minimum mandatory modifications for MARCH/CORRAL prior to use, plans for baselining MARCH/CORRAL for industry use, plans for integrating phenomenological model development into analyses and identify the desirability and directions for major upgrade of MARCH/CORRAL.

(2.) Containment Analyses

Perform analyses for representative containment/system types for dominant accident sequences and necessary variants.

(3.) MARCH/CORRAL Improvements

Define program for major development of MARCH/CORRAL model improvements and implement if desired.

(4.) Integrate Phenomenology Models into Analyses

Include the results of the phenomenological development activities into the integrated transient anlaysis.

(5.) EPRI/NSAC TMI Code

Qualify and document the PWR damage progression code. Develop, qualify and document the BWR damage progression equivalent code.

Budget/Schedule: The resources estimated for these activities are:

a. 5 MM contributory by interested parties

b. 24 MM and 100 CRU per plant type assuming results from on-going studies are applicable, assume three more types for a total of 72 MM and 300 CRU.

c. Major upgrade program would be 60-100 MM and 300 CRU. Should be undertaken only if directions indicate a real need for support of rulemaking in the March/April time frame.

d. 10 MM 20 CRU

e. 12 MM 30 CRU

OUT

TASK		RESOURCES MM	CRU	K$	Σ K$
1.		2			16
2.	(1.)	13	4		105
	(2.)	18	6		146
	(3.)	6			48
3.		11			88
4.	(1.)	18		40	184
	(2.)	24		75	267
	(3.)	10	20		86
5.	(1.)	15	20		126
	(2.)	30	20		246
	(3.)	8			64
6.	(1.)	3			24
	(2.)	12			96
	(3.)	3			24
7.		24	10		195
8.	(1.)	50	100		430
	(2.)	60	50	100	595
	(3.)	18			144
9.	(1.)	2			16
	(2.)	22	20		182
10.		3			24
11.					
12.		20			160
13.		8			64
14.		14	20		118

OUT

TASK		RESOURCES			
	MM	CRU	K$	∑ K$	
15. (1.)	--			--	
(2.)	72	300		666	
(3.)	--			--	
(4.)	10	20		86	
(5.)	12	30		105	
	474			4305	
IDENTIFIED CONTINGENCY	.			540	
				4845	
CONTINGENCY (15%)				5571	
PROJECT MANAGEMENT (20%)				6686	1115

APPENDIX A-2
EPRI PROGRAM - TECHNICAL DETAILS

DRAFT PROGRAM PLAN

Hydrogen Combustion and Management Studies
L. Thompson

1.0 Introduction

Hydrogen generation during a severe accident and its subsequent management pose many difficult questions. Postulated accident scenarios and complex LWR geometries can result in a wide range of situations, some of which would threaten the containment barrier if a deflagration or detonation is initiated. Combustion properties for hydrogen-air-steam mixtures in large scale with turbulence are not well known, and management systems must accommodate the hydrogen that is characteristic of both large and small break accidents, in atmospheres of various steam, gas and aerosol concentrations, at various pressures, and with the likelihood of substantial stratification and pocketing.

1.1 Objectives and Technical Issues. All technical issues regarding hydrogen combustion cannot be explored in depth in a reasonable time frame, nor would it be profitable to do so. This program will intend, rather, to meet the following limited objectives:

1. Determination of whether and when hydrogen can burn in various LWR accident environments resulting from 'Class 9' scenarios;
2. Demonstration that if a hydrogen burn does occur its effects will not exceed the realistic survival capabilities of equipment and containment; and
3. Demonstration that reasonable control methods can provide adequate safety margins assuring the integrity of the containment and of key safety-related equipment.

Determination of the containment and equipment capacity to survive potential threats due to hydrogen combustion requires investigation of several questions:

3. Experiments on hydrogen control methods including water spray and fog (Acurex);

4. Measurement and analyses of hydrogen mixing and distribution with natural and forced convection (HEDL-W); and

5. Demonstration of hydrogen combustion and management methods on a large scale turbulence (Nevada Test site).

Table I provides a capsule description of each program. Figure 1 shows realistic time scales for the projects, including the test phase (solid line).

2. Relationship of Program Elements to Technical Issues. None of the questions a-d above can be answered satisfactorily in any one facility due to questions of scaling or practicality. The need for near-term result in several areas also necessitates parallel efforts which employ the best features of each facility. Figure 2 illustrates the proposed use of facilities to answer the issues. The issues are briefly discussed below, and Tables II-VI expand on Figure 2 and describe how the various facilities can contribute in each case.

2.1 Lower Flammability Limits. The generally accepted lower flammability limit (LFL) of 4% hydrogen for upward propagation was derived from small scale eperiments in air [1-3]. The questions now concern the effect of vessel size and shape, igniter type, igniter location, turbulence, and steam (up to high concentrations.

In addition the use of water sprays, fogs, or other mitigation methods will affect the LFL at least for some conditions of flow rate and drop sizes and should be evaluated. Table II indicates the facilities which would be involved in the EPRI program.

2.2 Character of Deflagrations. The nature of deflagrations in LWR environments is influenced by many parameters. and careful selection is necessary to avoid an overwhelming matrix of cases for experimentation. For hydrogen concentrations above 10%, combustion is essentially complete,[4] and the burning rate in various environments and for various scales is of most interest. The transient pressure in the volume is related to the rate of deflagration which may be characterized by a burning velocity. The maximum burning velocity for hydrogen in air is found to be about 3.5 m/second in well-mixed quiescent atmospheres in small volumes[5,6] and it is known that diluents such as steam lower this value[7,8]

Questions involve the effects of hydrogen concentration, turbulence, steam, initial temperature, pocketing or nonhomogeneity, and water sprays, fog and other mitigation approaches. Table III indicates the potential research activities

2.3 Hydrogen Mixing and Distribution. The probable location and distribution of hydrogen in containment following a degraded core accident remains one of the most difficult questions. Data is needed for a variety of conditions so that computer codes which deal with natural and forced convection can be improved or validated. Quasistatic diffusion experiments have been performed, notably at Battelle-Frankfurt.[9] Battelle found that a temperature difference of less than 20 degrees F between upper and lower compartments of a 2500 ft^3 volume resulted in a significant segration of hydrogen. The lower compartment, occupying two-thirds of the volume and separated from the upper by an orifice of 10 ft^2 (1/100 of the area), reached a hydrogen concentration of 4% while the upper compartment saw only 1%. Experiments with a virtually homogeneous temperature resulted in uniform concentrations, and that result is confirmed by calculation [9,10].

The current questions relate to forced circulation and the dynamic effects of hydrogen jets, water sprays, and circulation fans in complex geometries, in addition to the effects of steam and imposed thermal gradients. Use of a compartmentalized volume which generically simulates a light water

a. What are the lower flammability limits in LWR accident conditions and how effective are various ignition sources;

b. What is the character of deflagrations in various LWR geometries and how can the effects be mitigated;

c. What is the nature of hydrogen mixing and distribution in large compartmentalized volumes with natural and forced convetion; and

d. What is the potential for the acceleration of deflagrations, or for "transition to detonation" in turbulent mixtures, and how can the effects of such explosions be mitigated.

Two additional research needs are implicit: (1) The development of predictive capabilities to allow extrapolation of test results to other geometries, scales, and environments; and (2) The assessment of hydrogen burn effects on safety-related equipment.

A very large data base does exist for combustion and for hydrogen in particular. That data base provides a starting point for investigation of the environments and geometries which are peculiar to LWR safety. The role of turbulence and dynamic phenomena on combustion during accident conditions is not well known, for example, and new data are needed to meet the objectives stated above.

1.2 Program Elements. Several projects are proposed which would provide the information needed to satisfy the program objectives. The projects are related, and consist of:

1. Development and preliminary testing of deliberate ignition systems (Rocketdyne Division of Rockwell);

2. Experiments and analyses on basic hydrogen combustion phenomena including the effects of steam, turbulence, and the potential for transition to detonation (AECL Whiteshell);

reactor would provide a helpful demonstration. Table IV indicates the facilities which could contribute in this area.

2.4 Transition to Detonation. It is well known that detonations are easier to produce in "shock" tubes or small volumes than in a large space. The classic "detonation limits" indicated by Shapiro and Moffette [11] are very uncertain. Hydrogen/air/steam conditions which fall within the detonation region may very well result in ordinary deflagrations, particularly if ignition is by a non-explosive trigger in an open volume [12-13]. Turbulence promoters such as a grid system (or stacked floor gratings), will accelerate a burn. Nevertheless it is expected that the most vulnerable regions will be in local structures such as protrusions from a larger volume.[14] Structures and equipment may also have a substantial capacity to survive a detonation since the pressure and temperature very quickly decays to deflagration levels, and hydrogen control means such as water sprays may sufficiently mitigate the phenomena. Table V indicates the research facilities which could study the potential for transition to detonation.

2.5 Effects of Burn on Safety-Related Equipment. The surviveability of safety equipment during a hydrogen burn is a serious question. The rapid decay of temperature and pressures plus the thermal capacity of much equipment creates a potentially favorable situation. Secondary fires initiated by a hydrogen flame front may be of greater danger. Pressure damage will depend on how well the equipment can "breathe". Safety-related materials and equipment can be placed in volumes to be used in combustion tests to help assess surviveability. Table VI indicates the facilities that could provide equipment qualification results.

3.0 Description of Program Elements.

Following is an expanded description of each of the five subprograms. The facilities and capabilities of each site are described in Appendices A-E.

3.1 Igniter Development (Rockwell/Rocketfyne). The task plan preparation is now underway, and involves establishment of requirements and combustion characteristics for various igniter types, including hot surface, spark, and combustion wave types. The testing system, igniter design, and experiment matrix will be defined in the initial project phase. Igniter and system fabrication, testing and evaluation will follow, with the emphasis on scoping the comparative effectiveness of the various igniter types in steam and water spray environments.

3.2 Combustion Studies (Whiteshell). A four-month period of tests will begin by April 1, 1981 to answer basic questions of combustion in a hydrogen/air/steam atmosphere. An 8-foot diameter sphere will be used for most of those tests, and a 5-foot diameter by 19-foot high cylinder is also available. The design pressure of 1450 psi will allow the occurrence of detonations, although none are expected.

Tests are being defined to study lower flammability limits in steam, laminar spherical deflagrations, and the effects of turbulence on deflagrations. In addition special tests such as ignition in one of two connected volumes will be performed. It is expected that about 50 tests can be performed in the four month perio with a high degree of flexibility. The test environment during this period will include the widest range of hydrogen/air/steam mixtures, but will not include water spray or other mitigation measures.

3.2.1 Lower Flammability Limits and Extent of Reaction. At concentrations near the LFL, i.e. less than approximately 10% H_2, the combustion reaction is not complete. These experiments can determine whether size and shape of the vessel affects the extent of reaction by comparing the results with those obtained previously at Whiteshell in a two-litre cylindrical vessel.

In these experiments, uniform hydrogen/air/steam mixtures will be spark-ignited at the bottom of the spherical vessel. By analysing the mixture before and after the experiment, using gas chromatography, the extent of reaction will be determined. Transient pressure and temperature measurements will be made and ionization probes will be used to detect flame speeds. Significant differences in the extent of reaction between the bench-scale cylinder and the eight-foot sphere may warrant subsequent experiments in the large cylinder. The flammability limits and extent of reaction depend on the location of the ignition source, and some experiments will be performed with central and top ignition which are known to be less effective in producing a reaction.

3.2.2 Laminar Spherical Deflagrations. At hydrogen concentrations greater than 10%, complete combustion is expected. Burning rates are important for determining possible blast effects at high flame speeds and for estimating the time during combustion that heat transfer can occur to reduce maximum pressures and temperatures. A correlation for laminar burning velocity as a function of hydrogen concentration and temperature has already been developed at Whiteshell based upon their bench scale experiments. This correlation allows a prediction of the pressure transient resulting from a laminar deflagration, and it is the intent of these experiments to validate those calculations.

Central ig[illegible]ion of uniform hydrogen/air/steam mixtures in the eight foot sphere will be p[illegible]ed for hydrogen concentrations in the range of 10 to 45%. Maximum burning velocities and the fastest deflagration transients are expected at 42% hydrogen. Detonations are not necessarily expected in this intermediate scale volume with a spark ignition source. High speed pressure and temperature transducers will record the transients and ionization probes will detect flame arrival.

3.2.3 Effect of Turbulence and Structures on Spherical Deflagrations. Since turbulence can significantly accelerate the combustion rate, experiments are proposed to examine this effect, somewhat qualitatively at this point. Turbulence in containments may be caused by convection currents from the ventilation fans and by obstacles (such as pipes, grids, etc). The proposed experiments would utilize: (1) a fan to produce convection flows prior to contral ignition of uniform hydrogen/air/mixtures; and (2) various structures or obstacles to determine their effect. The experiments would be performed in a manner similar to those described previously.

3.2.4 Special Tests. The Whiteshell high pressure sphere, pipe and cylinder can be combined in various configurations, which allows for several interesting possibilities. Unequal concentrations of hydrogen in different volumes can be separated by a weak diaphram, with ignition in one of the volumes. A 20-foot long 1 foot diameter pipe may also be connected to the sphere to evaluate the potential for local detonations in protrusions from larger volumes.

3.3 Control Studies (Acurex). The Acurex test vessel would be used for scoping mitigation phenomena such as the effects of water spray, fogs, and halon which will not be investigated in the near-term at Whiteshell. A bunkered data acquisition system is available, and remote operation from within the bunker will allow rapid turnaround between tests. Igniters developed and initially evaluated at Rockwell would be tested here in a larger volume with higher hydrogen concentrations.

3.4 Hydrogen Mixing and Distribution Studies (HEDL-W). Large scale near-term hydrogen mixing and distribution tests would be performed in the HEDL Containment Systems Test Facility (CSTF) to investigate aspects of hydrogen mixing, stratification and local accumulation. Efforts are expected to include mixing in the large open volume (30,000 ft^3) for baseline data, minimal compartmentalization to validate computer codes, and simplified configurations representative of LWR plants. Tests would be performed with and without containment sprays and steam, and would consider hydrogen mixing by both natural and forced convection. Measurement would be made of temperature, hydrogen concentrations, water/vapor concentrations, and convective gas flow patterns. The test results would be compared to pre- and post-test computer code analyses in an effort to validate and improve existing codes.

Compartments may be built outside of the CSTF and taken in through the large existing vessel door. Testing in the near term as planned will require use of only 4 volume percent hydrogen, however. Use of combustible mixtures would necessitate extensive safety reviews since the vessel is located in a building which houses other experiments. Tables VII and VIII outline the potential tests separated into natural and forced convection experiment series.

3.5 Large Scale Deflagration Tests. The Nevada test planning will incorporate results of the igniter development, combustion, control and distribution studies. The Nevada tests should demonstrate that the lessons learned at small scale apply to much larger scale, and that expected wide spread turbulence and non-homogeneity in an accident environment contribute no "surprises." Commercial-design containment sprays will be used, and a test matrix will be performed to verify deflagration limits and the effects of igniter location (and type), hydrogen concentration, and structures such as grids or obstacles. The effects of deflagrations on safety-related equipment can also be studied.

4.0 Estimated Program Costs.

Each of the programs outlined is intended to be flexible in terms of experimental activity, and costs can be adjusted accordingly. Table IX indicates the best estimates for the time periods shown in Figure 1.

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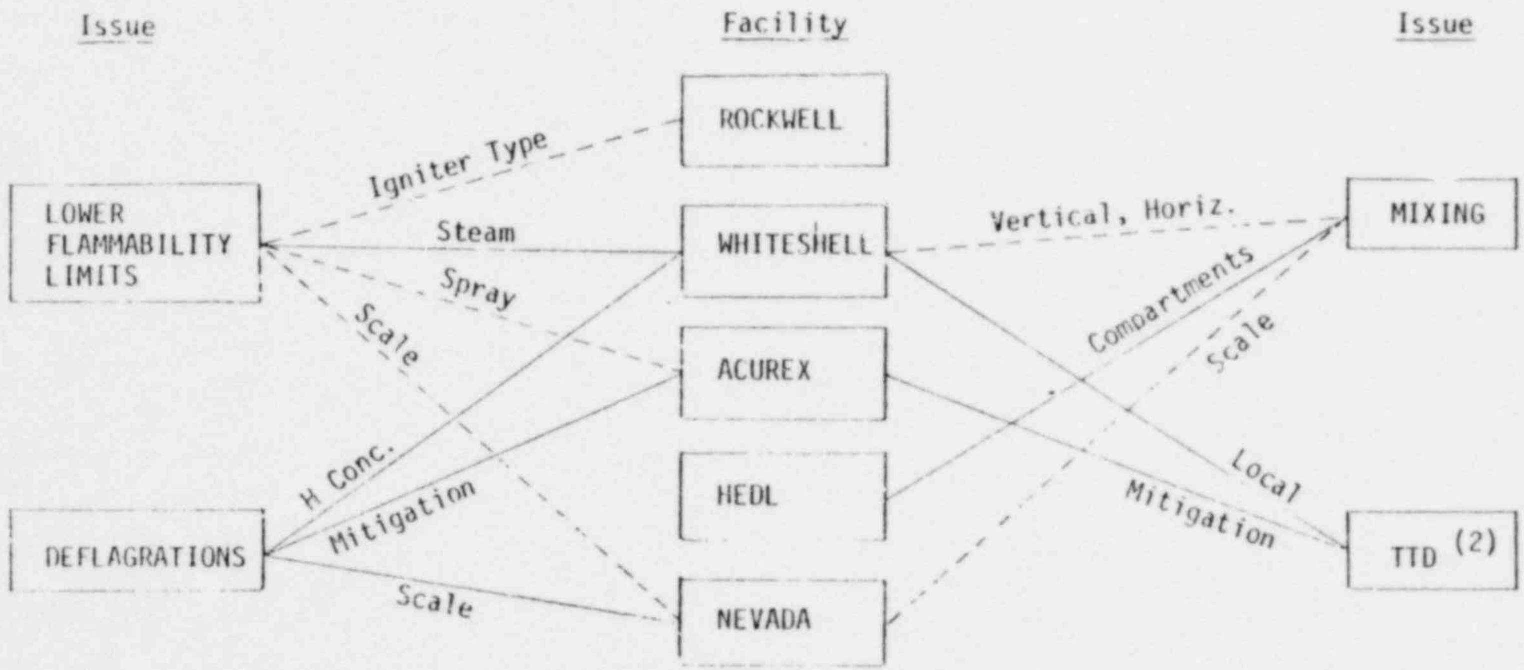
Figure 2

RELATIONSHIP BETWEEN TECHNICAL ISSUES AND EXPERIMENTAL FACILITIES [1]



(1) Key sites for Investigation are indicated by solid lines

(2) Rapid Deflagration, Quasi-Detonation, or "Transition to Detonation"

TABLE I

Options in Hydrogen Combustion & Management Program

1. Igniter Development (Rockwell)

Evaluation of techniques for ignition of combustible gases, including advanced methods developed for the U.S. space program. Goal is to obtain methods for reliable ignition of fuel-lean mixtures in atmospheres of hydrogen, air, and steam.

2. Hydrogen Combustion Studies (Whiteshell)

Basic studies of hydrogen combustion properties in a high pressure sphere and cylinder which can be connected by a variable length pipe. Associated modeling of burning velocities and gas dynamics, and small-scale model development tests.

3. Hydrogen Control Studies (Acurex)

Near-term exploration of various hydrogen management methods. Use of test site near EPRI and a surplus high pressure vessel with existing protected data aquisition system.

4. Hydrogen Distribution and Mixing Studies (HEDL)

A large cylindrical vessel with and without compartments, with various thermal gradients, atmosphere compositions, hydrogen injection rates, and use of forced convection generated by water sprays and fans.

5. Large Scale Deflagration Studies (Nevada)

Study of hydrogen deflagrations, and demonstration of management methods in a very large sphere, with and without compartments and water sprays, and with use of various ignition methods and locations, temperature gradients, and flame suppressants or water fogs. Demonstration that the small-scale database is applicable to "real" LWR accident conditions.

TABLE II

Lower Flammability Limits[1]

Parameter	Facility			
	Rockwell	Whiteshell	Acurex	Nevada
Volume (ft^3)	100	300	300	75,000
Igniter Type	Yes	No	Yes	Selective
Igniter Location	No	Some	Some	Yes
Steam	Yes	Yes	Yes	Yes
Turbulence	Yes	Yes	Yes	Yes
Non Uniformity	No	Yes	Yes	Yes
Water Spray	Yes	No	Yes	Yes
Halon	No	No	Yes	?
Key Measurements				
P,T, Conc.	Yes	Yes	Yes	Yes
Ion Probe	No	Yes	Yes	Yes
Approx. No. Tests	100	20	10	5

[1] Underlined items indicate key sites for investigation.

TABLE III

Deflagrations [1]

Parameters	Facility		
	Whiteshell	Acruex	Nevada
Volume (ft^3)	300	300	75,000
Hydrogen Concent.	Yes	Yes	Yes
Steam Concent.	Yes	Yes	Yes
Initial P and T	Yes	Yes	Yes
Turbulence	Yes	Yes	Yes
Pocketing	Yes	Yes	Yes
Water Spray	No	Yes	Yes
Water Fog	No	Yes	?
Halon	No	Yes	?
Structure Effects	Yes	Yes	Yes
Key Measurements			
P, T. Conc., Ion	Yes	Yes	Yes
Approx. No. Tests	30	15	5

[1] Combustion tests with hydrogen concentrations generally greater than 10%. Underlined items indicate key sites for investigation.

TABLE IV

Hydrogen Mixing and Distribution [1]

Parameter	Facility: Whiteshell	HEDL[2]	Nevada[3]
Characteristic Length (ft)	19 (Vertical) 50 (Horiz. Tube)	67 (Vertical)	52 (Diameter)
Volume (ft.^{3})	400	30,000	75,000
Compartments	Yes[4]	Yes[5]	?
Temperature Gradients	Yes	Yes	Yes
Steam	Yes	Yes	Yes
Water Sprays	No	Yes	Yes
Hydrogen Jets	Yes	Yes	No
Key Measurements:			
T, Concentration	Yes	Yes	Yes
Gas Velocity	No	Yes	No
Approx. No. Tests	5	20	20

(1) Underlined items indicate key sites for investigation.

(2) Limited to maximum of 4% hydrogen

(3) Distribution data obtained in conjunction with combustion tests.

(4) Compartment data can be obtained when sphere and cylinder are connected.

(5) Generic simulation of LWR possible.

TABLE V

Transition to Detonation (TTD)[1]

Parameter	Facility: Whiteshell	Facility: Acurex	Facility: Nevada[2]
Geometry	Cyl., Sphere, Tube	Cylinder	Sphere
Volume (ft^3)	300	300	75,000
Steam	Yes	Yes	Yes
Water Spray	No	Yes	Yes
Water Fog	No	Yes	?
Halon	No	Yes	?
Ignition in 'Compartments'	Yes[3]	Yes[4]	?
Structure Effects	Yes	Yes	Yes
Simultaneous Ignition	Yes	Yes	?
Ignition Power	No	Yes	No
Key Measurements			
P, T, Conc., Ion	Yes	Yes	Yes
Shadowgraph, Schlieren	Future	Possible	No
Approx. No. Tests	10	10	?[2]

(1) Underlined items indicate key sites for investigation.

(2) Demonstration tests using mixtures approaching the detonation region may be conducted if intermediate scale tests indicate TTD is very unlikely.

(3) Ignition in tube connected to large volume.

(4) Ignition in balloon or small compartment.

TABLE VI

Effects on Equipment(1)

Parameters	Facility		
	Whitesh	Acurex	Nevada
Volume (ft^3)	300	300	75,000
Deflagration	Possibly	Yes	Yes
Detonation	Possibly	Yes	No
Water Spray	No	Yes	Yes
Water Fog	No	Yes	?
Halon	No	Yes	?
Approx. No. Tests	?	10	10

(1)Underlined items indicate key sites for investigation.

TABLE VII

Hydrogen Mixing by Natural Convection

PURPOSE: The purpose of these experiments is to quantify the degree to which hydrogen mixes with the containment atmosphere when mixing is induced only by natural convection processes.

INFORMATION TO BE OBTAINED: These tests will measure the concentrations of hydrogen at strategic spatial locations as functions of time. This information will be analyzed in terms of a natural convection computer code which will allow the determination of turbulent diffusivities.

FACILITY REQUIREMENTS: These tests will employ low hydrogen concentrations (0-4%) and could best be done in the CSTF vessel at HEDL.

DESCRIPTION OF TEST SERIES: The mixing of hydrogen, introduced through porous plates at low velocity, would be measured under various thermal gradients. Saturated steam-air mixtures at various temperatures would be established, and then hydrogen would be introduced. Parameters would include atmosphere temperature, composition and temperature of hydrogen gases introduced, and duration of the injection period. The use of compartments and generic LWR structures would be planned.

TABLE VIII

Hydrogen Mixing Augmented by Forced Convection (HEDL)

PURPOSE: These tests will quantify the degree of hydrogen mixing which results when forced convection processes are present. Realistically, hydrogen will likely enter the containment atmosphere as a jet, sprays may operate or ventilation fans may operate. All of these processes augment hydrogen mixing and need to be accounted for.

INFORMATION TO BE OBTAINED: Hydrogen concentrations at various spatial locations will be measured as a function of time. Also gas velocities and directions will be measured at a few key locations. These data will be used to prove containment mixing codes, providing turbulent diffusivities and forced convection flow quantities.

FACILITY REQUIREMENTS: These tests could best be done in the CSTF vessel at HEDL.

DESCRIPTION OF TEST SERIES: These tests are quite similar to those of the previous series except that various mixing promoters would be operated. Several tests would be required to study the effect of mixing when H_2 was introduced as a circular jet. At least two tests would use containment sprays, one at ambient temperature and one at an elevated temperature. The use of compartments and generic LWR structures would be planned.

APPENDIX A-3
HALON STUDY - TECHNICAL DETAILS

II. TECHNICAL BACKGROUND

Before describing a Halon system we should give the basis for our opinion, mentioned earlier, that a 1301 system might be suitable for an ice condenser containment. It is based on the following simplified estimates: the total containment volume is taken as approximately 1.2 x 10^6 ft^3 which includes upper and lower compartments and ice condenser plenum and bed volume. We further assume approximately 1,200 lb mass of hydrogen to be produced, which by itself is equivalent to roughly 3 psi in the total containment volume. Based on results in the report cited below, it is estimated that about 175,000 lb mass of Halon would be required to inert the containment for these conditions. This is equivalent to approximately 6 psi of Halon, which now produces a total containment pressure of 9 psig and is less than design. However, we emphasis that these rough estimates are only meant to show first-cut feasibility of the concept. Note also that the heat to vaporize the total Halon inventory would be 6.2 x 10^6 BTU which is small compared with the blowdown energy or the heat of fusion of the total ice inventory.

Any water-cooled nuclear reactor in which a LOCA occurs can produce hydrogen gas by reaction of H_2O with zirconium and by radiolysis of cooling water by decay products. Explosive mixtures of hydrogen with the air of the containment can form. There are a number of possible means of providing protectio , and the method to be described here involves inerting the containme t with a gas known as Halon 1301, which chemically is trifluorobromometha e, CF_3Br. Atlantic Research Corporation over a period of nearly three years conducted a study of the use of Halon 1301 in the reactor containment for nuclear powered ships, under sponsorship of the Maritime Administration of the Department of Commerce ("Hydrogen Suppression Study and Testing of Halon 1301", by Edward T. McHale, Contract Nos. MA-6562, and T-38619, December 1976 and March 1978). Copies of these reports are being submitted with this proposal. In the ca e of the maritime reactor, a Halon system was found to be completely suita le and would have been the system of choice had such reactors been built. Much of the following information is drawn from the above-listed reports.

The suppresion system would consist of a predetermined quantity of Halon 1301 stored as a liquified gas in several storage vessels near the containment. In the event of a LOCA, if the hydrogen concentration reached some predetermined level, the 1301 would be discharged either automatically or manually into the containment through a piping and valve system. Many operational advantages are associated with the simplicity of a 1301 system. For example, there are few moving parts, minimal power requirements, high reliability, relative economy, storage convenience, ease of periodic testing, and once activated the system requires little further attention.

When Halon is mixed at the proper concentration with hydrogen/air or oxygen enriched air, it will render such mixtures completely nonflammable. Other gases such as nitrogen and carbon dioxide produce the same effect, although such large quantities of these compounds are required that the overpressure in an ice condenser containment (or probably any containment) would exceed design or even ultimate rating. The amount of Halon required for a given volume depends on the concentration of hydrogen and air, temperature, pressure, presence of steam, losses, etc. Experimental measurements have been made at Atlantic Research to map the complete flammability (explosive) diagrams for $H_2/O_2/N_2$ mixtures containing Halon 1301. It is virtually certain that once the hydrogen/air concentrations, etc., are known that the required amount of Halon could be specified with no further testing.

A great number of physical and chemical properties of an inerting gas must be considered before it can be selected for containment application. These involve materials compatibility, thermal stability, long term storage, toxicity, vapor pressure, critical temperature, solubility in H_2O, and others. Many of these are discussed in the above referenced report. In general, the properties of Halon 1301 are very favorable for containment use. There are, however, some questions concerning its radiolytic stability in water and the effect of decomposition products (if any) on metals. These will be specifically addressed in the present study. In addition to the above properties, the availability of Halon must be considered. It is presently marketed by DuPont under the tradename Freon 1301as a fire and explosion suppression agent, and its availability is not expected to be a problem.

There are certain questions about Halon behavior which are unique to a containment application. Some of these have been examined in our previous study and will be mentioned. One question that arose concerned the effectiveness of charcoal filters, through which the containment atmosphere is passed when being purged, to absorb iodine and methyl iodide radioactive fission products in the presence of Halon. Tests showed that air or H_2/air mixtures containing Halon would pass through the charcoal with no absorption of the Halon but with complete absorption of the iodine materials. It was also possible to show analytically that Halon and iodine compounds would not react with each other. Thus Halon mixtures, either following a LOCA, or in the event of accidental discharge, could be safely vented through a charcoal filter system.

Extensive studies were also conducted on the radiolytic stability of Halon in the radiation field of the containment. It was shown that in the containment volume proper, negligible radiolytic decomposition would occur. It was found, however, that if Halon could find a way to become exposed to the cooling water and to dissolve in it (solubility in the range of 100 ppm at 120°F and decreases with increasing temperature), the core radiation could decompose a small amount of the Halon. This loss should be allowed for during system design. In the case of the ice condenser containment, the small amount of decomposition may yield sufficient halide compounds dissolved in water to produce a deleterious effect (from a long range or recoverable point of view) on materials in the primary system. This is a key problem which will be carefully examined in the proposed study. It should also be mentioned that should this prove to be a problem there are means available to overcome it. For example, the decomposition reaction is self-arresting and there are additives which can bring about this arresting effect and retard any decomposition.

The foregoing discussion is meant to provide an indication of what a Halon inerting system would involve and of some questions (many of which have been answered) that can be raised about its operational features. Before ending this section it is desirable to outline in broad form what is required to be done to determine if such a system can be applied to an ice condenser containment. Very soon after a system study is initiated, technical personnel from Atlantic Research would visit a nuclear plant for a complete inspection and a briefing of all aspects of the reactor system and containment that are relevant to Halon application. Following this visit a preliminary working design of a Halon system would be devised. This would include full specifications of worst-case amount of hydrogen expected and amount of 1301 required for inerting (considering that required for safety margin and make-up for all losses - long-term leakage, radiolysis, dissolution, etc.) Pressure-temperature-time histories would be plotted using the COGAP and ARC computer codes. These codes would also yield the required rate of Halon injection to stay ahead of H_2 build-up.

Simultaneous with the system specification study we would begin to examine the potential problems that could initially be identified. These involve as a minimum Halon decomposition, water chemistry and materials compatibility with decomposition products. One question that had been raised concerned the ignition of inerted hydrogen mixtures using a shock wave initiation source. For example, if a pocket of H_2/air formed in an inaccessible section of the lower compartment and did not get inerted by Halon, what effect would it produce on the inerted containment mixture if it become ignited and sent out a blast wave. These and other questions will be addressed by literature search and analytical study using experts in each particular subject area.

III. PROPOSED WORK

1) A preliminary system design will be made which, while it will represent a working model, will nevertheless be complete. It will specify Halon quantity required, rate of discharge, H_2 build-up rate, pressure-time and temperature-time hi...ories, Halon losses from all known sources (leakage, radioysis, dissolution), contribution by Halon to blowdown energy removal, etc. (ARC and COGAP codes to be used.) The Halon hardware system will be specified to the extent of storage tanks sizing and number for redundancy, spray system configuration for thorough mixing and discharge rate, and distribution analysis of Halon throughout upper and lower compartments. Between two and four technical personnel will visit a nuclear plant with an ice condenser containment for one or two days of discussions early in the program.

2) The present flammability diagrams for $H_2/O_2/N_2$ mixtures containing Halon were mapped using the "strongest credible" ignition source which was represented by a squib igniter. It has been postulated that hydrogen might pocket somewhere in the lower compartment, not get properly inerted, and then ignite and produce a blast. Therefore, we will investigate by literature search and combustion analysis if it is known whether otherwise inert mixtures can be initiated with a blast wave. The question to be answered here is not whether mixtures can be inerted against shock wave initiation but rather how much extra, if any, 1301 agent would be required. In this task, as in others requiring literature search, we will use our own background knowledge of sources plus the Atlantic Research DIALOG computer search facility which has the capability of examining numerous sources of technical literature.

3) The amount of Halon decomposition that will occur in the ice condenser containment due to dissolution in H_2O and radiolysis from the core will be computed. This is obtained by calculating the total decay energy from which is obtained the accumulated radiation dose per NRC guidelines. Then knowing Halon partial pressure, G-value, and decomposition rate functional dependence the total integrated amount of decomposition can be computed.

4) Study the change in water chemistry due to Halon decomposition and

its effect, if any, on materials of construction in the primary system. Examine in detail methods of inhibiting decomposition by additives if necessary and the effects of additives on water chemistry and their materials compatibility. Corrosion and degradation of properties of metals in the primary system will be the main concern. Literature searches will be conducted to determine if changes in such properties as tensile strength, elongation, elastic modulus, etc., have been studied when metals are exposed to low concentrations of halides in water at elevated temperature and pressure.

5) The above list of problems is preliminary and other items to the studied are likely to be discovered when the various topics are examined in detail.

Two technical reports will be submitted in the course of the work. At the mid-point of the study an interim report will be prepared outlining progress to date on each topic. At the completion of the program a final summary report will be submitted which will present complete results and their interpretation together with recommendations. The program manager will deliver the final report to the sponsor and make an oral presentation of results.

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November 26, 1980

Dr. Wang Lau
Tennessee Valley Authority
400 Commerce Avenue
Knoxville, TN 37902

Reference: Contract TV-55205A - "System Feasibility Analysis of Using Halon 1301 in an Ice Condenser Containment"

Dear Dr. Lau:

This summary letter report is being submitted per the contract requirement to provide an interim report in the course of the program. Up to the present time a visit was made to the Watts Bar plant by five technical persons associated with the study, numerous telephone discussions have been held with TVA, AEPSC and Duke Power personnel, and a group from Duke Power visited Atlantic Research for a review of the Halon system and our opinion about alternative approaches.

We have had requests to accelerate progress if possible, which we are trying to accommodate but, as explained, much of the work follows a sequential path and certain tasks cannot be completed until other prior work has been performed.

In broad summary, it can be reported that a Halon 1301 system is certain to be able to provide full safety against any possible hydrogen hazard following a LOCA in an ice condenser containment. The matter that remains does not concern safety acceptability, but rather concerns the question of how much corrosion might certain materials be subjected to, and will the primary and secondary systems meet specifications and be recoverable after a LOCA if they were exposed to Halon decomposition products.

Briefly, the corrosion problem is as follows: Halon itself is stable and inert toward materials. However, if needed following a LOCA, Halon gas could dissolve to a small extent in the emergency cooling water (its solubility is 150 ppm by weight in water at 77°F and 0.5 atm). Radiolytic decomposition can then occur, the result of which could be the formation of bromides (and fluorides) in low concentration (about 400 ppm Br^-) in the water. Therefore, the question being addressed is what effect such a solution will have on reactor materials, particularly stainless steels.

If unfavorable answers emerge from the materials study, then the options are the following:

- Plan to install a Halon 1301 system to provide safety during the interim while an alternative system is being developed, using the rationale that the likelihood of having to employ Halon is extremely small.

- Study the effect of exposure of stainless steels to hydrogen. Since hydrogen has an embrittling effect on steels, it may be that hydrogen alone is deleterious enough that the reactor system could not be recovered anyway, even if Halon were not used.

- Investigate means of eliminating or reducing the effect of bromides. The general approach would be to find additives that defeat the Halon radiolytic decomposition mechanism in solution. Several candidate approaches have been considered:

  - Determine if Halon decomposes in solution in the presence of hydrogen as rapidly as in its absence. Hydrogen may compete with Halon for solvated electrons, the species responsible for initiating Halon degradation.

  - Add an additive to the water that will precipitate bromide in inert form. (A search for candidate additives will be made.)

  - Add an additive to the water that will produce hydroxyl radicals in solution. These radicals are thought to react with bromide ions to reverse the decomposition reaction. Alcohols may be good candidates.

  - Determine whether decomposition of Halon will occur to the same extent over a range of pH values.

  - Generally attempt to find additives that may be effective in reversing Halon degradation.

Substantial progress has been made on three tasks of the program and each of these is reviewed below.

System Design

If no credit is allowed for steam inerting, it will require 191,600 lb mass of Halon 1301 to inert the total containment, including upper and lower compartments and ice condenser plenums (1.2×10^6 ft^3). The Halon requirement is derived from the flammability data obtained in the previous ARC study and the assumption of 75% zirconium cladding reaction releasing 1450 lb mass of hydrogen. Assuming negligible losses and specifying a 20% excess, the total Halon requirement will be 230,000 lb. Neglecting losses is justified because the containment leak rate is essentially zero, and the loss to cooling water is 4540 lb via Halon decomposition and 880 lb through dissolution. The containment partial pressures will be (70°F basis):

Air	1.000 atm = 14.70 psia
H_2	0.234 atm = 3.44 psia
Halon	0.493 atm = 7.25 psia
	1.727 atm = 25.33 psia = 10.7 psig

A storage and piping configuration has been designed which is based on the guiding principle that the system must function properly even if two independent malfunctions occur simultaneously. The Halon would be stored in five 316 stainless steel tanks, four of which would contain the required 230,000 lb and an identical fifth back-up tank would contain 57,500 lb. The storage tanks are sized to contain the Halon at temperatures in excess of 130°F where the liquid density is 77.6 lb/ft^3. Each tank would have an equivalent spherical diameter of 12 feet with a wall thickness of three inches. This provides a working pressure of 600 psig for the system, conforming to Section VIII of the ASME Unified Pressure Vessel Code.

Each tank would have an associated tank of nitrogen gas connected to it which would maintain a delivery pressure of 600 psig if the Halon had to be discharged. The five Halon tanks are valved independently to two manifolds of four-inch SS Schedule 40 pipe. (The manifold piping diameter may have to be larger if a total run of much more than 300 - 400 feet is required.) Two penetrations of the containment will be required for the four-inch pipes. The piping will conform to ANSI B-31.10 classification. Inside the containment, the piping branches to the upper and lower compartments, each accumulator compartment and the instrument room to maximize coverage of isolated compartments.

An array of spray nozzles comes off each manifold pipe inside the containment. The requirement is to deliver 230,000 lb Halon in 1000 seconds or 1330 gpm at 130°F. One arrangement to accomplish this is to use 20 full cone nozzles of 15/32" orifice on each manifold, one of which is sufficient. This feature of the system design is being left open at present. The exact nozzle system configuration would have to be determined by actual inspection of the containment and computation of the requirement in each area.

The final report will present the system design in much greater detail. Other aspects of the design are also being worked on, including instrumental analysis requirements.

Halon Decomposition and Bromide Ion Concentration

Since the net decomposition of Halon ceases at equilibrium Br^- concentration of 5.2×10^{-3} moles/l, the total quantity of Halon decomposed depends (at equilibrium) upon the total quantity of water in the containment (6.46×10^{-3} lbs Halon decomposed per gallon of water). For the maximum amount (702,950 gallons, re: TVA letter of Oct. 31, 1980), the quantity of Halon decomposed is 4540 lb, independent of the fission product release to the water. An additional 880 lb will remain dissolved in the water.

The rate of Halon decomposition also depends upon the quantity of water in the containment. The time-dependent quantity of Halon decomposed for several potential values of the containment water inventory has been computed and will be given in the final report.

Decomposition of Halon yields Br^- in solution which acts as a scavenger for the OH radical and tends to suppress further Halon decomposition. Equilibrium is attained at a Br^- concentration of 5.2×10^{-3} moles/liter also.

Water Chemistry and pH

Br^- is presumably formed as [illegible] and decomposition of Halon also produces HF at concentrations 3 times that of HBr. HF ionization, however, is suppressed by the H^+ from HBr ionization, and at equilibrium most of the HF is undissociated.

The pH changes depend upon the initial chemical composition and pH of the water in the containment system. Although the system water will likely be slightly alkaline (pH >7) and perhaps buffered (presence of sodium borate, for example, to prevent criticality), calculations of the pH changes have been made conservatively assuming pure water (pH of 7.0) in the containment system initially. Assuming complete ionization of HBr and an ionization constant of 3.53×10^{-4} for HF, the resulting pH at equilibrium would be -2.2, determined principally by the HBr, with HF ionization largely suppressed.

Ignition of H_2-Air-Halon Mixtures by Shock

Hydrogen-air mixtures can be inerted against combustion by addition of Halon 1301, and a large body of data on the flammability limits of such mixtures has been developed previously using sparks and squibs as ignition sources. The question has arisen as to whether a shock wave could ignite mixtures that are so inerted. In order to answer this question, a literature search is being conducted to determine if the matter has ever been studied, and an analysis of the hydrogen combustion chemistry is being performed. To date, the literature search has not turned up any direct information. The analytical work, although still incomplete, is indicating that once inerted against sparks or pyrotechnic ignition, a mixture cannot be shock initiated. This is the type of question that lends itself to analytical study wherein definite conclusions are possible because hydrogen-oxygen combustion is the best understood of all fuel systems.

In addition, we are examining the question of what structural effects would be expected from explosion of uninerted pockets of H_2-air of various dimensions.

Very truly yours,

ATLANTIC RESEARCH CORPORATION

Edward T. McHale

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ETM/bls

cc: Stephen J. Miloti
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