MONTHLY PROJECT STATUS REPORT
September 15, 1983

Report No. RDA-MR-127300-003
Period Covered: July 30 through August 31, 1983
Name of Program: Severe Accident Mitigation Systems
Contract Number: NRC-03-83-092
Start Date: June 27, 1983 Completion: 27 months

SECTION A: Technical Summary of Project Status

Technical progress has been good and active work continues on Tasks 1-5. (Task 6 is done only on specific assignments). As agreed to at the kick-off meeting (7/12/83), the first specific containment type to be studied in Task 3 is the Mark II BWR, as exemplified by the Limerick plant. We have been requested to make a special rapid response on our study of this type plant by January 1, 1984. This mini-study will include assessments based on Task 1, 2, 3, and 4 activities, and thus represents the first priority of activity for all tasks.

During August substantial progress was made on reviewing Mark II containments and their failure modes, including preliminary assessment of dominant risks, possible mitigation schemes, and a preliminary value/impact range. Several types of mitigation systems were selected for preliminary design and costing. These were chosen on the basis that systems having unequivocable modes of performance should be the standard against which other systems, having greater operational uncertainty, should be compared. These comparisons, and the final selection of a system for design, are expected to be accomplished during October. An addendum to this monthly report provides a summary of preliminary value/impact assessment being performed under Task 4 for the Mark II mini-study. This assessment provides an estimate of the range of costs that can be supported for mitigation, (including not only equipment but procedures and outage costs). Another addendum is a draft version of the cumulative mitigation requirements for the Limerick plant. It is by no means final at this time.

The conference on LWR severe accident evaluating was attended by W.E. Kastenberg and I. Catton. A meeting of BNL, NRC, Purdue and RDA was accomplished during the conference. A report on the meeting will be forwarded under separate cover. At the request of Dr. J. Meyer, I. Catton attended a meeting on MFIIOR. His report on the meeting will also be forwarded under separate cover.

For Tasks 1 and 2 the process of data collection is well along, outlines have been made of the topical reports, and some text preparation has begun. A special list of all known mitigation proposals, devices, and systems was prepared and delivered to NRC; a copy is attached. The report outline for Task 3 is currently being revised, and procedures and outlines for Tasks 4 and 5 are being prepared.

The Master Plan outline for the project is under way, and is expected to be completed during the current period. NRC has designated GESSAR as the second of the three types of containment to be studied in Task 3. Plans are being made to visit the Perry plant during the current period.

For the purposes of our contract "mitigation" has been defined as those actions, devices, components and systems that deal with events and their consequences *after* the core is melted. This definition is quite straightforward except in the case of failure to scram. For a BWR under certain conditions (Class IV) a large steam spike could rupture the containment long before core-melt occurred. Similarly, there are some sequences (Class II) wherein the containment fails prior to core melt, but on a long time scale. We have requested written instructions on how to interpret these special cases. It is feasible to include a mitigation system for an ATWS event (probably a vent), but it has been our impression that prevention of an ATWS would be more cost-effective than mitigation, and that the Limerick plant had already been modified to reduce such events to a non-dominant risk level (the so-called 3-A fix). The significance of ATWS to mitigation will be clarified in the near future.

SECTION B: Technical Status by Tasks

Task 1. Survey of Containment Systems. This task comprises data gathering, categorization of dominant accident sequences, and evaluation of mitigation opportunities for the major types of reactor containment. The work will be organized and reported by containment type, *viz.* Mark II, Mark III, GESSAR, etc. Thus the work on Mark II containment will form a chapter both in the Mark II mini-study and in the topical report for Task 1.

a. Efforts completed: Assessment of Mark II containments and the severe accident research literature has been completed. Work on the other pressure-suppression types is well underway. Personal contact and telephone interviews have been made with research investigators in the field at

Sandia, Brookhaven, and Purdue.

b. Problems or delays: None.

c. Summary to date: Data collection mostly complete for pressure-suppression containments, well underway for other types. Review of accident sequences is complete for BWR's, just beginning for PWR's. Identification of mitigation opportunities is complete for Mark II containments, underway for other pressure-suppression types.

d. Plans for next period: Meetings have been scheduled with representatives of Sandia, Brookhaven, and Purdue to discuss and coordinate our survey with current research efforts. It is planned to finish source collection, finish assessment of Type I and Type II containments, and begin work on PWR containments. Text preparation will also begin.

<u>Task 2. Survey of Mitigation Systems.</u> a. This task will survey a wide range of concepts, proposals, devices, and systems for mitigating the consequences of severe accidents. These will be categorized into groups by function, and ranked according to feasibility, cost, etc. The specific devices, sub-systems, etc., to accomplish a given function, such as core-retention or heat removal, are designated as *components*. A selection of appropriate components will be made to form a mitigation *system* suitable for each major containment type as determined in Task 1.

a. Efforts completed: Tabulation of mitigation concepts applicable to Mark II containments has been completed. A complete list of all known suggestions for mitigation systems or components has been completed and submitted (see Addendum).

b. Problems or delays: None.

c. Summary to date: The information collection phase of this task is nearly complete. Assessment and ranking of the material is under way. An outline of the final report has been prepared and written text is being prepared. Information concerning mitigation components for Mark II plants has been transmitted to the other task efforts.

d. Plans for next period: Complete collection of data, continue assessment and ranking of mitigation components.

<u>Task 3: Design and Feasibility.</u> This task comprises selection of up to three major types of reactor containment with the approval of the Project Officer, establishing for each type the requirements for a mitigation system in view

of the dominant risks established in Task 1, and choosing a suitable combination of components as characterised in Task 2. After establishing by preliminary analysis in Task 4 that the functions chosen to be performed would likely have a suitable effect on overall risk and with enough design effort to show probable feasibility, a final selection of a mitigation system will be made with the approval of the Project Officer. Then a complete conceptual design, cost and feasibility assessment will be performed.

a. Efforts completed: Based on Task 1 results, the requirements for mitigating the residual risk in Mark II containments have been established, subject to some remaining uncertainty as to whether ATWS events are considered to have been prevented or are to be included in the mitigation category. Preliminary design and costing has been made for several possible mitigation systems (combinations of components). These are now undergoing evaluation before final selection and presentation to the Project Officer.

b. Problems or delays: None.

c. Summary to date: For Mark II containment as exemplified by the Limerick Plant, mitigation requirements (functions) have been identified, including containment heat removal, core residue capture and retention without concrete attack, and (if ATWS events are to be mitigated) some kind of venting system. Candidate components to fulfill these requirements have been selected for preliminary conceptual design and cost estimation. Separate cost figures will be generated for 1) Plants before construction begins, 2) Plants built but not yet in operation, and 3) Operational plants.

d. Plans for next period: Complete preliminary designs and assessments for Limerick, and begin final design of selected version.

Task 4: Value/Impact Analysis. This task will provide a quantitative assessment of the relative risk that can be averted by mitigating particular aspects of the containment failure. It will determine whether a proposed mitigation system is cost effective, and which components are most important.

a. Efforts completed: Collection of source documents for Value/Impact evaluation is virtually complete. The recent Boston meeting on Severe Accidents will provide additional material. Copies of the most important papers are already available. Previous Commission statements and action in the

Value/Impact evaluation is virtually complete. The recent Boston meeting on Severe Accidents will provide additional material. Copies of the most important papers are already available. Previous Commission statements and action in the field has been reviewed including the PNL Value/Impact Handbook under development for RSR Division. A preliminary Value/Impact analysis for the Limerick plant was initiated using the BNL review of the Limerick PRA and the new PECO PRA. The results of this analysis are summarized briefly in the Addendum attached to this report.

b. Problems or delays: None.

c. Summary to date: Methodology for Value/Impact analysis of mitigation conceptual designs is being formulated, based on prior work in the field and the specific requirements of this task. A preliminary analysis for the Limerick plant has been completed.

d. Plans for next period: A working procedure for assessment will be put into preliminary operation for examination of Mark II mitigation schemes. This procedure will be discussed with NRC before final adoption.

<u>Task 5:</u> <u>Licensing Strategy Development.</u> This task will assist the NRC in utilizing the results of this project by developing suitable methodology and strategies for assessing and implementing severe accident mitigation policies.

a. Efforts completed: Collection and review is under way of suitable documents, reports, and prior action of the NRC, especially SECY-82-1-A and -82-1-B, and NUREG 0933.

b. Problems and delays: None.
c. Summary to date: Background and criteria under development.

d. Plans for next period: Continue development.

<u>Task 6:</u> <u>Consultation and Special Assignments.</u> No effort has been assigned by NRC to this task so far.

ADDENDUM TO MONTHLY REPORT

September 15, 1983

Value/Impact for Limerick Mitigation

In order to obtain a range of possible acceptable costs of mitigation for the Limerick plant, two estimates were made using the proposed trial goal of $1,000/man rem averted as follows:

ESTIMATE NO. 1

The first estimate uses the data contained in the BNL review (NUREG/CR-3028) of the Limerick PRA. Note that this data does not reflect external initiators. The Limerick PRA and the BNL review conclude that the majority of latent effects (and population dose) result from containment failure via slow overpressurization (Class I).

In Table 1, the contribution to latent fatalities for the dominant releases are shown as well as their frequency. The expected value is 0.174 latent deaths/year. Of these 0.166 latent deaths/year come from OPREL, the Class I sequences described above. Using a conservative conversion factor of 2×10^{-4} latent deaths/man rem (linear dose model, no threshold) and an allowed cost of $1,000/man rem, one obtains an upper limit cost of 33.6 million dollars.

ESTIMATE NO. 2

The second estimate uses the data contained in the new Limerick PRA which includes external events, but not the modifications to frequency and consequences contained in the BNL review. The new PRA indicates that fires and internally initiated sequences contribute about equally to latent effects (Class I slow overpressurization). Seismic events contributing to Class IV (ATWS events) are also important contributors to latent fatalities. Early fatalities still continue to be dominated by Class IV events (ATWS) but seismic vessel failure also becomes an important contributor.

Accidents initiated by fires fall into existing release categories. Random vessel failure and accidents initiated by earthquakes required new release categories.

The sequences which are affected by fires are QUX, QUV and QW, which increase the OPREL (Class I) release category significantly. The seismic initiators lead to case with various combinations of vessel and containment failure due to the seismic event itself. For those cases where the containment does not fail seismically mitigation is possible.

Using the data contained in the PRA, 220 man-rem/year can be averted if containment failure due to slow

overpressuriation (only) is eliminated (perfectly). At $1,000/man-rem and a 40 year life, the allowable cost is 8.8 million dollars.

DISCUSSION

The values estimated above (8-33 million) are ball-park estimates and are subject to change dramatically pending (a) the BNL review of the new PRA, and (b) new work on the Source term.

At present they are only for use as guidance in the design of mitigation. A target of 15 million dollars will be used for screening purposes.

TABLE I

Category	Frequency (per year)		Latent deaths		
OPREL	7.7×10^{5}	x	2.2×10^{3}	=	16.6×10^{-2}
R_{2a}	9.8×10^{-8}	x	2.1×10^{4}	=	20×10^{-4}
R_{2b}	2.1×10^{-8}	x	1.8×10^{4}	=	3.7×10^{-4}
R_{2c}	3.2×10^{-9}	x	1.8×10^{4}	=	0.58×10^{-4}
R_{2d}	4.3×10^{-7}	x	6.6×10^{3}	=	28×10^{-4}
C_4	1.4×10^{-7}	x	1.4×10^{4}	=	1.98×10^{-3}
$C_4\gamma'$	7.1×10^{-8}	x	1.4×10^{4}	=	9.98×10^{-4}
$C_4\gamma''$	7.1×10^{-8}	x	1.3×10^{4}	=	9.21×10^{-4}
					17.43×10^{-2}/yr

CUMULATIVE LIST OF MITIGATION REQUIREMENTS FOR MARK II

The dominant severe accident sequences for the Mark II Boiling Water Reactors result in a small number of final end states wherein the containment is breached. To consider mitigation of these end states, it is necessary to assess them in a cumulative fashion. Thus, if any of them result in a plant having a tctal electrical failure, then all mitigation schemes considered must work in this environment. If any of them will undergo failure by overpressure, then all systems must be able to protect against this failure, etc. On the other hand, if none of the dominant sequences include seismic failure of the containment structure, then we can assume that it is intact for purposes of mitigation, and so on. Following are a brief list of assumptions and policies on which a mitigation design might be based, followed by a tentative set of cumulative requirements for the Limerick plant, derived by assessment of its dominant failure modes. In C. are listed the end point conditions in the containment under the cumulative worst case accident sequences. A mitigation concept that could cope with these conditions would necessarily handle the lesser, more probable events.

A. Ground-rules and Assumptions for Mitigation Design

1. When the behavior of the core or other material is in an uncertain or debatable situation, the uncertainty will be avoided by designing that situation out of the sequence. If this is not possible, the uncertainties will be reduced to the maxiumum amount possible.

2. Passive action will utilized wherever possible, but where it technically is impossible or unreasonably costly, a fully independent and redundant source of energy will be used.

3. If the containment is not overpressured, it is assumed that the water in the suppression pool will not escape, although it might drain partially into the secondary containment building to the level of the lowest penetration.

4. The containment will not fail to isolate, or changes will be made to insure isolation on demand.

5. An intact containment always presents less risk than an opened one.

6. A system that segregates and confines radioactive materials into a definite, enclosed region presents less human risk than one that spreads it over several regions.

B. Cumulative List of Mitigation Requirements.

1. If risk assessment indicates that early containment failure from an ATWS is a dominant (>1%) part of total risk, then a vent system of some type is required.

2. Reliable, redundant cooling of the containment is required even though there is no electric power.

3. The molten core debris must be provided an unequivocable pathway to a location where it can be retained and cooled indefinitely.

C. Assumed Initial Conditions at Time of Meltdown.

1. All electric power has been lost, both on-site and off-site.

2. The suppression pool has been heated by a turbine trip from full power. If an ATWS has occurred, the pool is saturated at the vent pressure.

3. The normal and emergency core-cooling systems are inoperative.

4. The emergency heat removal system is inoperative.

5. The core has boiled dry and is in the process of melting its way through the bottom of the vessel.

6. More than 50 tons of molten steel will accompany the core into the sub-vessel area.

7. All the zirconium in the core has reacted to form hydrogen.

After further refinement and developent of these ground rules and conditions, they will be used to specify the design of specific mitigation systems under Task 3.

PROPOSED SEVERE ACCIDENT MITIGATION SYSTEMS

The following list is fairly comprehensive as to types of proposed remedies, but does not attempt to include every variation, modification, and repetition within each type. No classification was made as to feasibility, effectiveness, or cost of the proposed systems.

I. CORE RETENTION DEVICES

1. Water-cooled crucible: A metallic container fitted with a water jacket and placed to intercept molten core material that has escaped from the reactor vessel or from the containment. In one version the crucible is retrofitted to an operating plant by tunneling below the basemat, and cooled by passive thermal siphons.

2. Flooded thoria rubble bed: A bed of refractory pebbles is placed on the floor of the reactor cavity, with water circulating through the bed.

3. Water-cooled refractory tiles: Similar to the pebble bed but consisting of interlocking tiles with cast-in water passages.

4. Pebble-bed covering cooling coils: A metallic piping system with a pumped water supply, placed in the bottom of the reactor cavity and covered with high-density refractory pebbles.

5. High-alumina cement covering cooling coils: A cast-in-place cement liner for the reactor cavity, with imbedded cooling coils.

6. Magnesium dioxide covering cooling coils: Cooling coils covered with interlocking magnesia refractory brock.

7. Zirconium dioxide covering cooling coils: As above with a different refractory brick.

8. Graphite covering cooling coils: Cooling coils covered with graphite or carbon brick. Sometimes with an outer cover of steel to prevent water contact.

9. Borax bath: A thick layer (12 ft) of borax bricks sealed in stainless steel, covering the bottom of the reactor cavity.

10. Heavy metal bath (lead, uranium, or copper): Cooling coils at the bottom of the reactor cavity, covered with a foot or so of lead bricks, or other metal. The lead will melt and transfer heat to the coils, but remain in place since it is denser than UO_2.

11. Iron oxide: A layer of iron oxide over cooling coils has been proposed, with the purpose of diluting the urania to lower its viscosity and increase volume and heat transfer surface.

12. Basalt concrete and basalt rubble bed: Basalt is soluble in molten urania, and the intention is to provide a dilution of the core material.

13. Sand core retention system: A very large mass of sand is provided below the containment building to absorb the heat of the core material and disperse it over a large volume.

14. Iron core retention system: A large mass of iron is provided to receive the core material and dissipate its heat.

15. Flooded cavity: Water is added to the reactor building to flood the entire cavity up to the vessel and even above it, in the hope that the core material will be kept dispersed enough to remain quenched.

16. Other active cooling systems: A number of special jackets and piping system in and around the reactor vessel have been proposed, with the intention of retaining the molten core within the reactor vessel.

II. OVERPRESSURE CONTROL FROM HYDROGEN OR HYDROGEN BURNING

1. Oxygen exclusion: The containment is operated with an atmosphere of nitrogen or carbon dioxide, or even vacuum.

2. Oxygen removal: Oxygen is removed from the containment when core damage is detected, using a combustion system or chemical absorbant.

3. Oxygen dilution: The oxygen content of the containment is diluted below the flammable limit with Halon gas, water fog or mist, foams, or sprays.

4. Igniters: Glow plugs or spark igniters are placed throughout the containment to burn hydrogen before it reaches an explosive concentration.

5. Fans: Rapid mixing of the containment air is proposed to prevent local accumulation of explosive hydrogen mixtures.

III. OVERPRESSURE CONTROL FROM ATTACK ON CONCRETE

1. Special concrete composition: The reactor cavity and basemat would be made with special concrete that does not release much noncondensible gas when attacked by core debris.

2. Thin basemat: Make the central part of the basemat thin to promote rapid escape from the containment building.

IV. OVERPRESSURE CONTROL BY VENTING THE CONTAINMENT BUILDING

1. Non-filtered vent: The containment is vented through a tall stack when it reaches a dangerous pressure.

2. Vent to receiver: The containment venting is connected to another large, closed building to provide a larger total expansion volume and greater cooling. A companion reactor containment has been proposed for this use. The receiver could also be an inflatable building or balloon, kept normally empty.

3. Vent to a condenser-filter: A large variety of condenser filter systems have been proposed, such as sand beds, gravel beds, water-sprayed gravel beds, scrubbers, gravel/sand, water pools, sand filters, charcoal filters, chemical scrubbers, all in various combinations.

V. OVERPRESSURE CONTROL BY CONTAINMENT HEAT REMOVAL

1. Heat pipes: Passive devices that absorb heat from vapor or pool space inside containment and release it externally through an evaporation-condensation exchange with an internal fluid.

2. Modified heat pipes: Heat pipes having separate liquid return passages, heat pipes with ganged penetrations, and variable gas-controlled heat pipes.

3. Heat exchangers: Standard cooling coils acting as condensers or pool coolers, with pumped external cooling fluid.

4. Spray coolers: Pumped sprays inside containment, combined with heat exchangers in the loop.

5. Fan coolers: Circulating fans combined with heat exchangers to increase thermal transfer from containment vapor space.

6. Secondary suppression pool: Provide a larger secondary suppression pool to increase heat capacity of system.

7. More reliable residual heat removal system: Increase the redundancy and ruggedness of the residual heat removal system.

VI. CONTAINMENT PROTECTION AGAINST MISSILES

1. Missile shields: Various structures designed to protect the containment penetrations or walls against flying debris or thrashing pipes inside the containment.

VII. SPECIAL CONTAINMENT STRUCTURES

1. Underground siting: Location of the containment vessel in an underground cavern or excavated pit, completely isolated from the external environment.

2. Berm shield: Partially underground containment building, protected by a earthen wall or berm. Sometimes a gravel bed is included for a filtered vent pathway.

3. Double containment: A second strong containment building surrounding the original containment has been proposed.

4. Strength improvements: For improving the pressure rating of an existing containment building, wrapping with wire, adding steel ribs, etc., have been proposed.

5. Increased volume: Increase the free volume of the containment building on new reactors.

6. Strengthen safety system: Make the essential safety systems more rugged by means of armor, bunkers, and heavier construction.

VIII. FISSION PRODUCT REMOVAL SYSTEMS

1. Containment spray systems: It has been proposed to decontaminate a containment building post accident with an elaborate spray system to wash down the interior with special solutions, and a treatment system to remove the contaminants from the solutions for use.

2. Gas treatment system: Provide a special recirculating treatment system to remove fission products from the containment gas volume.

IX. PORTABLE OR ADAPTIVE RESPONSES

1. Pumps: Use of portable pumps, fire trucks or fire boats to add water to the containment, keep a gravel vent bed wet, or for other requirements.

2. Earthmovers: Use of bulldozers, etc., to build up protective shields or berms around contaminated buildings, prevent flood erosion, etc.

R & D Associates
August 24, 1983