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UNITED STATES OF AMERICA
NUCLEAR REGULATORY COMMISSION

BEFORE THE ATOMIC SAFETY AND LICENSING BOARD

In the Matter of	)	
	)	
OFFSHORE POWER SYSTEMS	)	Docket No. STN 50-437
	)	
(Floating Nuclear Power Plants)	)	

NRC STAFF'S RESPONSES TO QUESTIONS POSED BY THE LICENSING BOARD IN ITS MARCH 29, 1979 LETTER

by

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Question 1

Both documents refer to WASH-1400 a number of times. In detail, to what extent did that document form the basis for conclusion in these documents?

Response

The major conclusions of the FES III for OPS relating to core melt risk relied upon qualitative factors and judgments which were supported by quantitative evaluations where possible. The thrust of the qualitative factors identified can be found on page 2-5 of the FES III "the staff finds two significant qualitative differences relative to the consequences of a core melt accident at floating and land base plants: (1) large quantities of radioactivity from the floating plant are likely to reach the open hydrosphere than from the land base plant, and (2) the radioactivity from the floating plant reaches the surface water sooner than from the land base plant." In addition on page 2-6 it states "the second significant qualitative difference between the two plants is the time for radioactive material to reach the liquid pathway. For the floating plant, the core debris and sump water is released to the surface water and transport processes would proceed immediately. Interdiction to confine the release to the immediate site area would not be expected in time to prevent transport of significant amounts of radioactivity to the open water body. For the land base plant, containment of core debris by the soil-rock foundation materials would act to slow the transport of radioactivity. Timely interdiction to confine the release to the immediate site area could reasonably be expected at most land base plant sites."

As noted in the FES III (pp. 3-1, 3-11, 3-13, etc.) calculations were performed to help characterize the significance of these noted differences. In performing these calculations, the best information and techniques available were utilized. In some cases when the air pathway consequences related to core melt accidents were being evaluated, WASH-1400 methods were utilized. Where more recent information was available it was utilized. The FES III noted the uncertainties associated with the methods and results of WASH-1400 and recognized the need for caution in uncritically using the results of these calculations. The following is a list of major aspects of the analyses which utilized WASH-1400 methods and results.

1. Core melt probabilities in the LPGS and FES III were estimated based on the results of WASH-1400 and on more recent results obtained from the reactor safety study applications program which included recent analyses of

the ice condenser design. While WASH-1400 was used in an attempt to quantify the differences in core melt scenarios between the FNP and other light water reactor designs these differences were recognized in a qualitative way independently of the work of WASH-1400. For example, the likelihood of containment failure by over pressure for the low design pressure small volume ice condenser containment is greater than for the typical high pressure containment PWR design for similar accident scenarios.

2. The source terms for both the liquid and air pathway releases in the LPGS and FES III were based upon the work of WASH-1400. This included the fraction of activity in the containment sump water, the fraction of activity in the molten core debris at time of melt-through, and the amount of radioactivity in the containment atmosphere available for release. WASH-1400 was utilized as a reasonable characterization of this distribution of radioactivity. It was known and recognized from other less detailed methods what the distribution of radioactivity in those media would be. For example, the TID source term utilized in our accident analysis as part of the safety review assumes 50% of the radioactive iodine from the core is released to the containment atmosphere. The ice in the ice condenser or spray for the containment would remove most of this activity and it would end up in the sump water. In addition, it is known that other volatile isotopes such as Cesium would be transferred to the sump water to a significant degree. Thus, although WASH-1400 was used to arrive at a quantitative estimate of the fraction of core inventory for a given isotope in the different media,

engineering judgment also provides a reasonable estimate of the relative distribution of activity in these media. These judgments clearly show that a large fraction of the volatile non-noble gas activity (e.g., iodines and Cesium) would be available for release in the sump water, that most non-volatile activity would remain in the core debris, and that the gases and a fraction of the volatiles would be available in the containment atmosphere. These judgments led to the Staff conclusion that a core melt on an FNP could result in a release of a significant quantity of radioactivity to the liquid pathway both from the core debris through leeching and from release of the sump water.

3. The air pathway consequences for land based and floating plants using the WASH-1400 methods and results were utilized as an aid in evaluating the significance of the relative risk determined for the liquid pathways (page 3-13). These results were not key to the primary conclusions discussed above; however, they were useful in developing a better understanding of the relative significance of these conclusions.

4. 1400 methods were utilized in an effort to quantitatively compare the costs associated with air pathway impacts from core melt accidents for land base and floating plants. These air pathway costs were utilized as an aid in developing a perspective on the significance of the liquid pathway costs

associated with the floating and land based plants. The costs associated with the liquid pathway were not determined using the techniques, methods or results of WASH-1400 and they played a more significant role in arriving at the conclusions of the FES III.

5. The air pathway interdiction methods which were discussed in FES III were obtained primarily from the WASH-1400 report. As in 4 above the air pathway results did not play a key role in the decision making process but rather a supplementary role. Many of the methods and techniques for interdiction of the air pathway which were discussed are founded not solely on the work of WASH-1400 but rather on known sound principles of interdiction upon which the WASH-1400 report itself was based.

As can be seen from the above discussion, WASH-1400 played a significant role in our attempts to quantify many of the risk factors associated with core melt accidents in this comparative study. However, these quantitative estimates were not key to the decision making process but rather supportive and confirmatory to the qualitative judgments and conclusions reached by the Staff. As noted on page 3-46 of the FES III, the Staff conclusion results from our determination that it is not feasible to successfully accomplish source isolation of releases for the presently designed open breakwater FNP design so as to limit the relatively rapid release of activity to the liquid pathway; whereas effective source isolation is feasible for most land based plants. This is a subjective judgment based upon reasonable engineering principles, experience in related fields, and a knowledge of the general processes that would be involved in a core melt accident.

Question 2

"Conservative" assumptions as opposed to most realistic assumptions are often applied (e.g., LPGS, pp. 4-4, 4-9, 4-12, 4-13, 4-17, 5-3). Did these assumptions then influence the weighing of alternatives and the cost-benefits balances?

Response

A thorough knowledge of the behavior and distribution of important parameters and the way in which they interact would likely result in somewhat different numerical results than reported in the LPGS and FES III. Our investigations of the sensitivity of the numerical results to such variations indicates, however, that the subjective interpretation of these results would not change. Therefore, it is the judgment of the Staff that the primary conclusions stated in 1 above would not be altered.

As discussed in 1 above, the conclusions reached in the FES III were primarily judgmental in nature and relied upon quantitative assessments of accident impacts and cost-benefit balancing as aids in developing a perspective on the relative significance of these judgments. In performing these quantitative assessments, in many cases, analyses were performed using single point estimates. This was found necessary because of a lack of definitive data in a given area or as an aid in simplifying an otherwise highly complex problem. As noted in the FES III, the variations of important parameters were considered and in many cases, parametric evaluations performed in an effort to appreciate the significance of the point analysis performed.

In the FES III, the comparison of LBP with FNP was limited to comparison of essentially side-by-side plants. We did not rely on a comparison of a typical LBP river site with an FNP estuary site. Thus, many of the "conservatisms" in the dispersion and dose models were effective for both types of plants.

Question 3

Why were staff models (LPGS Appendix B) developed only for fresh water? Marine models were purportedly covered in "OPS, 1977" but a more specific reference is not cited. What is it?

Response

It is the Staff's understanding that the reference cited is entitled "OPS Liquid Pathway Generic Study, Topical Report No. 22A60, June 1977" by the Applicant, Offshore Power Systems. This document covers the models used for the majority of the dose calculations in the ocean FNP case in the Staff's "Liquid Pathway Generic Study," NUREG-0440.

The Staff developed the models for all land based sites, including estuaries. In addition, the Staff's estuary model was used for the side-by-side comparison of the FNP versus the LBP in the estuary in the Staff's LPGS, NUREG-0440 and the OPS, LPGS. Topical Report 22A60.

The Staff performed additional modeling on the FNP in estuaries and ocean for the Final Environmental Statement Part III on Floating Nuclear Power Plants (NUREG-0502), which were not reported in the LPGS. These models consider the effects on aquatic organisms of large radioactive releases to the water from core melt accidents at FNP's.

Question 4

What reasons were there for not considering interactions with sediment in off-shore cases (LPGS, p. 4-13)? Since we believe consideration should have been given, what are the effects of such interactions?

Response

While certain possible effects of sediment interactions for the ocean FNP site were not discussed in the Liquid Pathway Generic Study (NUREG-0440), consideration was given to such interactions in the FES Part III (NUREG-0502), Sections 3.4.2.1 and 3.4.3.1. The Staff estimated that up to 0 5 percent of the radioactivity that could be released from the FNP would be "scavenged" if high levels of sediment were present in the water column due to a recent or coincident storm with moderate waves. The Staff concluded that there would be localized mortalities to demersal organisms and eggs due to the contaminated sediments. Doses to man from organisms contaminated by radioactive sediments were not explicitly considered since 99.5% of the released radioactivity would be in the dissolved phase.

Calculation of doses to man for the ocean FNP case took into account the contribution of shine from beach sediments made radioactive by contact with contaminated seawater (OPS 77, Section 6.3). The Staff concludes that this aspect of the dose model is conservative. Sensitivity analyses for all LBP models in the Staff LPGS indicate that sediment sorption always has the effect of lowering the population dose, even though the environmental contamination may be prolonged. The same conclusion should hold true for sediment effects in the marine environment.

The Staff previously estimated that the quantity of core debris particles which could escape the breakwater was insignificant compared to the quantity of dissolved radioactivity sorbed on the naturally occurring sediments. The Staff analysis did not, however, consider in detail all potential mechanisms for suspension and transport of fine particles within the breakwater. Such mechanisms include thermal currents caused by the heat of the debris, wave induced flow velocities and floatation by noncondensable gases.

Particles once outside of the breakwater would behave differently than dissolved radioactivity, both mechanically and biologically. The path and speed of their dispersion would be different, and the greatest movement would most likely occur during storms. Particles may be more radioactive and be more persistent sources of external radiation since their dispersion would be slower than that of the dissolved radioactivity. Calculations using this higher external radiation might indicate increased mortalities to demersal organisms. However, the coincidently calculated doses due to dissolved radioactivity would be smaller if it is assumed that much of the radioactivity remains in the particles.

The Staff and Applicant intend to investigate the ramifications of particulate radioactivity to the ocean based FNP and relate these to the analyses already reported in the Liquid Pathway Generic Stucy (NUREG-0440) and Final Environmental Statement Part III (NUREG-0502). More specifically, by letter dated June 14, 1979, the Staff has requested the Applicant to provide its analysis of this matter. We will then conduct our own independent review of the ramifications of particulate activity and will report back to the Board as soon as that review is completed.

Question 5

Iodine appears to be one of the most serious contaminants in a major accident. For example, Tables 2.4.3 and 2.4.4 estimate releases of about 1000 ci. How effective is the waste system in collecting radio-iodine from sump water? How is the chemical speciation of iodine predicted?

Response

As discussed in Section 2 of the LPGS, for a number of specific design basis event sequences (accidents) the potential release of liquid radioactive wastes was evaluated. Some of these events resulted in large quantities of radioactive iodine contained in liquid waste, usually in the reactor building sump. When needed for reactor cooling, this contaminated sump water is circulated through the core. At some point after an accident, however, cleanup of the contaminated water would be initiated. The radioactive sump water can be directly transferred to the radwaste storage and processing system. There is no direct path by which the water could be discharged from the plant.

The only credible pathway for discharge of liquid radwaste from the plant is the liquid radwaste discharge line. The liquid discharge line is provided with multiple valves to reduce the possibility of an inadvertent release to the environment. There are two manual block valves, a manual flow control valve, an automatic isolation valve that closes on radioactivity above a predetermined value, and an isolation valve that closes on low dilution flow in the cooling water system. In addition, the radwaste storage tanks are located in the hull of the FNP with compartments which are separated from the outer hull by two intervening water tight bulkheads. Spills, overflows, or tank ruptures regardless of size would not result in liquid being released to the environment. The FNP radwaste system is designed to process radioactive liquid waste through the use of demineralizers, filters, holdup tanks and evaporators. Liquid can be recycled through the system as many times as necessary to achieve the desired purity of the effluent. The system can reduce the concentration in contaminated water to levels within the 10 CFR Part 20 concentration limits.

While the calculated radiological consequences of inadvertent liquid discharges can be equal to or greater than the air pathway for the same accident, the multiple failures and operator error required for such a release led the Staff to the conclusion that the liquid pathway risk is lower than the air pathway for design basis accidents.

Concerning the speciation of iodine, iodine is a prominant member of fission product decay chains having masses of 127, 129, 131, 132, 133, 134 and 135, and is a minor product, largely formed by neutron activation, for masses 128 and 130. Over one third of all fission events involve a product which eventually decays into or through iodine isotopes. Kilograms of iodine isotopes, predominantly stable ^{127}I and very long lived ^{129}I, are present in a typical power reactor core.

Chemical changes in the fuel associated with fission favor the iodine to be in the form of the iodide, with very much smaller amounts of elemental idoine and hypoiodite, and concentrate the iodine species, particularly the lower mass isotopes, at or near the fuel pellet surfaces. In damaged fuel, steam and hydorgen release iodine as hydorgen iodide, which is a gas readily soluble in water and a moderately strong acid. Hydrogen iodide reacts readily with many metals and painted surfaces forming stable iodo-complexes and organic iodide addition compounds, a process referred to as "plating out" (i.e., the attachment of iodine to surfaces). Due to the high solubility and reactivity of hydrogen iodide, it is conservative to assume that 25% of the released radioiodine inventory initially exists as elemental vapor within the containment atmosphere.

Oxygen in air can oxidize iodide to elemental iodine, so it is necessary to control the acidity and oxidation potential of post accident sump solutions to reduce the vapor pressure of dissolved iodine species.

There is little propensity for the formation of volatile organic iodides, e.g., methyl iodide, in a light water reactor, since carbon is present only as a trace impurity. The atmosphere, however, contains a few parts per million of methane. The assumption that 4% of the airborne iodine exists as methyl iodide is consistent with the efficient reaction of this trace of methane in the containment atmosphere with the iodine. Since methyl iodine is comparatively insoluble in water and comparatively poorly absorbed on charcoal, it is conservative to assume as much of the iodine as possible is in this form, and to ignore the decomposition of methyl iodide by radiolysis, photolysis, and reaction with steam.

Factors which favor the existence of iodine in aqueous solution by reducing its vapor pressure are alkaline conditions (high pH), the presence of reducing agents (e.g., hydrazene, dissolved hydrogen), and the presence of dissolved iodide (the formation of triiodide ion).

References:

L. F. Parsley: Chemical and Physical Properties of Methyl Iodide and its Occurrence under Reactor Accident Conditions (A Summary and Animotated Bibliography) ORNL-NSIC-82 (Dec. 1971)

R. J. Davis: Mechanisms of Sorptium of Moleculer Iodine ORNL-4126 (Aug. 1967)

R. H. Barnes: et al, Chemical-Equilibrium Studies of Organic-Iodide Formation Under Nuclear Reactor Accident Conditions, BMI-1781 (Aug. 1966), BMI-1816 (Sept. 1967), BMI-1829 (Feb. 1968)

Question 6

How important is iodine in the overall assessment of Liquid Pathways following a Class 9 accident? What chemical species will iodine form, and how is each species treated in the model?

Response

Radioiodine releases to the liquid pathway were found not to be of major concern in the assessments of the core melt accident. The radioiodines contained in the core, with the exception of a small amount (approx. 3 curies) of I-129, are all short half-life nuclides - I-131 (half-life of 8.05 days) is the longest lived radioiodine present. For radioiodines to contribute a significant detriment to public health and safety exposure pathways must exist with a short response time and high utilization. These conditions are met in airborne releases where the inhalation pathway and exposure to surface depositions can hardly be avoided - except by evacuation of the potential receptors. There exists no comparable exposure pathways in the liquid environment. The liquid pathway of shortest response time is the shoreline sediments - analogous to the airborne surface deposition. However, movement of individuals a hundred feet from the shoreline would essentially eliminate the exposure.

Iodine released to the liquid pathway would have been volatilized from the core and removed from the containment atmosphere by the containment spray system. It is expected that the iodine will be in either the iodide (I^-) or iodate (IO_3^-) form due to chemical additives in the spray waters to enhance removal from the containment atmosphere. Both of these forms exist in the aquatic environment.

The biota uptake model used in the liquid pathway consequence analysis did not include consideration of radioiodine species. Although there have been suggestions that these considerations may have a role in the global iodine cycle, the biological uptake of iodine is generally considered not to be influenced by speciation. The extensive information on mammalian iodine uptake, covering a wide range of chemical forms inhaled or ingested, indicates no chemical species effects.

The significance of radioiodine released to the liquid pathway is limited by the radiological half-life and the response time of the pathways. Interdiction of exposure pathways, highly feasible over the radioiodine lifetime, would further reduce the contribution. In view of these considerations and the lack of any indication that radioiodine speciation is significant in biological uptake, the Staff considers that the consequence model employed provided an adequate input into the assessment of the risk associated with potential releases to the liquid pathway.

Question 7

Are bioaccumulation factors such as those in LPGS, Table C-4 affected by chemical speciation? Will isotopes leached from a core melt take the same speciation as natural elements?

Response

The elemental bioaccumulation factor is defined as the ratio of the concentration of the element in an organism to the ambient water concentration. For stable elements an equilibration between the various environmental compartments (water column, sediments, trophic level, etc.) and chemical speciation can be assumed. Thus, the actual source of the element to the organism, e.g., ingested or taken up directly from the water, and its chemical form need not be known. Under similar conditions the concentration of a radionuclide in the organism can be predicted from knowledge of the analog elemental bioaccumulation factor and the water borne concentration of the radionuclide.

The bioaccumulation of a radioisotope may be different from that indicated by the elemental factor for various reasons. For example, the elemental factor would overestimate the uptake if the dynamics permitted significant radiological decay. Underestimation could result if the released radionuclide entered and resided in an environmental compartment with an increased availability relative to the stable element. The reverse is also possible. Chemical speciation consideration could play a similar role. Based on our current understanding of aquatic food chains and environmental chemistry, the possibility of an over or under prediction by the elemental bioaccumulation factor cannot be ruled out.

Identification of the speciation associated with the elements leached is not generally available from the literature. These concerns are of secondary importance in the quantification of the leach release in view of the variability in the experimental leach data. However, as the basic mechanism of the leach process is elemental, not isotope specific, and the origin of the water borne natural elements lies with a similar leaching process, one might assume ultimately similar speciation. Although speciation might be a factor in determining the potential radiological risk from releases to the hydrosphere, there is insufficient information to model this aspect, in terms of the speciation at the release, changes in the environment, and the significance in the exposure pathways.

GORDON L. CHIPMAN, JR.

PROFESSIONAL QUALIFICATIONS

ACCIDENT ANALYSIS BRANCH

DIVISION OF SITE SAFETY AND ENVIRONMENTAL ANALYSIS

Since February 1976, I have been a Section Leader in the Accident Analysis Branch, Division of Site Safety and Environmental Analysis, U.S. Nuclear Regulatory Commission. In this capacity, I supervise the evaluation of reactor siting and radiological safety, and the development and evaluation of analytical models used in design basis and realistic accident analysis. I have participated heavily in the development of new or revised Regulatory Guides and Standard Review Plans. On numerous occasions I have made presentations to the ACRS and testified at ASLB hearings. I had primary review responsibility of the risks associated with the Floating Nuclear Power Plant.

I attended the University of Nebraska where I majored in Electrical Engineering and participated in the Navy Regular ROTC program. I graduated with a Bachelor of Science degree and was commissioned as a regular officer in the United States Navy in June 1965. Additional graduate level studies in nuclear reactor theory, health physics and related engineering fields were completed in 1966 at the Officer Naval Nuclear Power School, Mare Island, California. I subsequently studied and qualified as a Senior Reactor Operator at the Naval Reactors Nuclear Power Facility in West Milton, New York.

My association with the Naval Nuclear Propulsion program provided me with five years of professional experience in the nuclear field, primarily

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with pressurized water reactors. I have been qualified as a Senior Reactor Operator on three Navy nuclear propulsion plants. For two years I was assigned to an operating nuclear submarine, during which time my duties included directing, training and supervising technicians in the operation, maintenance and repair of various equipment and systems, including the nuclear propulsion plant. Starting in 1969, I was assigned to the crew of a nuclear submarine under construction. My duties included supervising the Electrical Division and the Reactor Control Division, testing of the nuclear propulsion plant, directing and supervising technicians in the inspection, testing and operation of various equipment and systems and training of technicians for examination and qualification as reactor operators and various other operating positions. In 1970 I was assigned as an instructor in advanced tactics at the Officers Submarine School where I instructed and trained the officers of nuclear submarines.

I joined the Regulatory staff of the Atomic Energy Commission in September 1972 as a reactor engineer. Since then I have participated as an Environmental Project Manager in the analysis and evaluation of the environmental features of design of the Dresden Units 2 and 3 facilities. As a Project Manager in operating reactors, I participated in the review and evaluation of safety considerations associated with the design and operation of several licensed power reactors. Subsequently and prior to joining the Accident Analysis Branch, I participated in the analysis and evaluation of engineering safety features of design of power reactors under license application review. I have been particularly closely associated with the reviews of the Westinghouse Electric Corporation's Reference

Safety Analysis Report, RESAR-41, and Boston Edison Company's Pilgrim Nuclear Generating Station, Unit 2 and the preapplication review of South Carolina Electric and Gas Company's Virgil C. Summer Nuclear Station Unit 2.

PROFESSIONAL QUALIFICATIONS
OF
ANDREW R. MARCHESE

I am a Reactor Engineer with the Office of Nuclear Reactor Regulation, U. S. NRC. For the past four (4) years at NRC, one of my principal areas of responsibility is to perform consequence evaluations of low probability core meltdown accidents. This work includes the evaluation of all aspects of the reactor containment building response to postulated core meltdown events, including the associated materials interactions between core melt debris and various containment materials. In the case of Floating Nuclear Plants (FNP), I was the principal NRC staff member who performed independent analyses of: (1) the penetration of core melt debris through containment materials, including refractory sacrificial materials to delay melt-through; and (2) the leach releases of fission products from core melt debris to the underlying basin water.

Prior to employment with the NRC, my professional experience includes: two (2) years with the U. S. Atomic Energy Commission, Division of Reactor Development and Technology as a Systems Engineer where I was responsible for providing technical supervision of contractor personnel for the design, development, construction, testing and operation of assigned reactor plant fluid and mechanical systems for the Liquid Metal Fast Breeder Reactor (LMFBR) Demonstration Plant; five (5) years with Atomics International as a Member of the Technical Staff where I was responsible for performing heat transfer and fluid dynamics studies on advanced nuclear reactor systems; and two (2) years with General Dynamics as a Thermodynamics Engineer.

My education includes an M.S. degree in Mechanical Engineering from the Massachusetts Institute of Technology and a B.S. degree in Mechanical Engineering from the Pennsylvania State University. In addition, I have completed extensive graduate course work in the Nuclear and Mechanical Engineering Sciences at the University of California, Los Angeles and San Diego.

I am a member of three American Nuclear Society (ANS) Standards Committees (ANS-54, 54.1 and 54.6) which are developing safety criteria and standards for advanced reactor systems. I am a member of the Sigma Gamma Tau National Engineering Honorary Society. My awards include a High Quality Performance Award from the U S. NRC, a National Science Foundation Fellowship to MIT, and an Academic Achievement Award from the Pennsylvania State University.

A list of papers which I have either authored or co-authored is provided on a separate sheet of paper.

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PUBLICATIONS

1. "Radiological and Containment Analyses for a Postulated Fast Reactor Melt-Through Accident with Containment Venting" (co-author), International Meeting on Fast Reactor Safety Technology, Seattle, Washington, Paper No. C-221, August 12-23, 1979.

2. "Sensitivity Study of CRBRP Containment Response to a Core Meltdown Accident" (co-author), International Meeting on Fast Reactor Safety Technology, Seattle, Washington, August 19-23, 1979.

3. "Molten Core Debris-Reactor Material Interactions" (co-author), The American Ceramic Society, Inc., Fall Meeting, San Diego, California, October 25, 1978.

4. "Interactions Between Molten Core Debris and Reactor Materials" (co-author), ANS 24th Annual Meeting, San Diego, California, June 18-22, 1978.

5. "Interaction Between Molten Core Debris and Containment Materials" (co-author), ANS Winter Meeting, San Francisco, California, November 27-December 2, 1977.

6. "Licensing Views on Post-Accident Heat Removal," Post-Accident Heat Removal Information Exchange Meeting, Argonne National Laboratory, Symp. Vol. November 2-4, 1977.

7. "Assessment of CRBRP Containment Response to a Hypothetical Core Melt-Through Accident" (co-author), ANS 23rd Annual Meeting, New York, N. Y., June 12-16, 1977.

8. "Licensing Decisions and Safety Research Related to LMFBR Accidents" (co-author), International Conference on Nuclear Power and Its Fuel Cycle, Salzburg, Austria, Paper No. IAEA-CN-36/576 (IV. 2), May 2-13, 1977.

9. "Influence of Rod Spacers on the Heat Transfer to a Liquid Metal Flowing In-Line Through a "Closely Spaced Rod Bundle," Liquid Metal Heat Transfer in Nuclear Plant Components Symposium, 14th National ASME-AIChE Heat Transfer Conference, Atlanta, Georgia, ASME Paper No. 73- HT-59, August 5-8, 1973.

10. "Experimental Study of Heat Transfer to NaK Flowing In-Line Through a Tightly Packed Rod Bundle," AIChE-ASME 13th National Heat Transfer Conference, Denver, Colorado AIChE, Paper No. 36 (Aug. 1972).

11. "Analytical Study of Heat Transfer to Liquid Metals Flowing Parallel Through Tightly Packed Fuel Rod Bundles," Liquid Metal Heat Transfer and Fluid Dynamics Symposium, ASME Winter Annual Meeting, New York, N.Y., Symp. Vol, page 15 (Nov. 1970).

12. "Optimization of a Nuclear-MHD Topping Cycle," M. S. Thesis, MIT, Cambridge, Mass., Sept. 1966.