IDR6 Iodine Release

SECRETARIAT RECORD COPY

The American Physical Society

AMERICAN PHYSICAL SOCIETY STUDY GROUP ON RADIONUCLIDE RELEASE FROM SEVERE ACCIDENTS AT NUCLEAR POWER PLANTS

Chairman: Prof. Richard Wilson
Department of Physics
Harvard University
Cambridge, MA 02138
617-495-3387 or 2866
FTS: 830-3387 or 2866

Executive Assistant: Dr. Kamal J. Araj
Department of Physics
Harvard University
Cambridge, MA 02138
617-495-3339
FTS: 830-3339

Executive Secretary: Ms. Diane Rolinski
Department of Physics
Harvard University
Cambridge, MA 02138
617-495-3387 or 2664
FTS: 830-3387 or 2664

Members: Dr. Augustine O. Allen
P.O. Box 173
Shoreham, NY 11786
(516) 744-2302

Prof. Peter Auer
Lab. of Plasma Studies
Cornell University
Ithaca, NY 14850
(607) 256-4366, 4023 or 3623

Prof. David Boulware
Department of Physics
University of Washington
Seattle, WA 98195
(206) 543-8591

Dr. F. Finlayson
Aerospace Corporation
P.O. Box 92957
Los Angeles, CA 90009
(213) 648-7120

Prof. Simon Goren
Dept. of Chemical Engineering
University of California
Berkeley, CA 94720
(415) 642-4574

Dr. Clark Ice
786 Boardman Road
Aiken, SC 29801
(803) 648-4640

Prof. Leon J. Lidofsky
Department of Aplied Physics and Nucl. Engineering
Columbia University
New York, NY 10027
(212) 280-4460

Dr. Allen Lee Sessoms, Director
Office of Nuclear Technology and Safeguards, Rm. 7828
U.S. Dept. of State
Washington, DC 20520
(202) 632-3310

Dr. Mary Shoaf
Plasma Physics Lab.
P.O. Box 451
Princeton University
Princeton, NJ 08544
(609) 683-2104

Dr. I. Spiewak
Institute for Energy Analysis
P.O. Box 117
Oak Ridge, TN 37830
(FTS) 626-3342

Prof. Thomas Tombrello
California Institute of Technology
Pasadena, CA 91125
(213) 356-6811 x 4581

R

15 February 1985

Dear Commissioner

I enclose a copy of the proposed press release, executive summary and conclusions of the APS report on the "source term." Copies of the full report will be hand delivered to the NRC offices at 1717 H St., NW on Tuesday, 19th February or Wednesday, 20th February.

We propose and hope you agree, to keep this confidential until the morning of Thursday 21 February when we will report to you in person.

Yours sincerely,

Richard Wilson
Mallinckrodt Professor of Physics
Chairman, APS Source Term Study Group

6/8

2-15-85

The American Physical Society

AMERICAN PHYSICAL SOCIETY STUDY GROUP ON RADIONUCLIDE RELEASE FROM SEVERE ACCIDENTS AT NUCLEAR POWER PLANTS

For further information contact Frank Ingram, Nuclear Regulatory Commission, Washington, DC, Tel. (301) 492-7715

PRESS RELEASE

APS STUDY GROUP DELIVERS REPORT ON RADIONUCLIDE RELEASE FROM SEVERE NUCLEAR REACTOR ACCIDENTS

WASHINGTON, DC
21 February 1985

New calculations indicate that for many of the ways in which a severe nuclear reactor accident might occur (postulated accident scenarios or sequences) the quantity of radionuclides that would reach the environment (i.e. the "source term") is much lower than that predicted ten years ago in the earlier Reactor Safety Study (RSS) of 1975, often called the Rasmussen Report. This reduction is attributed to three principal factors:

1. The recognition that reactor containment buildings are stronger than assumed by the RSS, and therefore fail, if at all, at later times.

2. The inclusion in the modeling of previously ignored physical and chemical phenomena which lead to the retention of fission products.

3. The inclusion of additional sites which trap radionuclides more efficiently than previously assumed.

One mechanism that might, for some rare sequences, increase the radionuclide releases above those calculated in the Reactor Safety Study is the release of non-volatile radionuclides as the moltent reactor core interacts with the concrete basemat. For this and other reasons, the study group found it impossible to make a sweeping generalization that the calculated "source term" would always be a small fraction of the fission product inventory at reactor shutdown.

These are the principal conclusions of a report delivered to the Nuclear Regulatory Commission today by a study group of the American Physical Society.

The American Physical Society were requested "to review the adequacy of the technical database, upon which models for calculating such accidents are constructed."

After the accident at Three Mile Island it was observed that much less radioactive iodine was released than had been expected in an accident of this magnitude. This prompted an international study to examine whether the same conclusion could apply to other situations.

The study group included: Richard Wilson (Harvard University); Kamal Araj (Harvard University); Augustine Allen (Shoreham, NY); Peter Auer (Cornell

University); David Boulware (University of Washington); Fred Finlayson (Aerospace Corporation); Simon Goren (University of California, Berkeley); Clark Ice (Aiken, South Carolina); Leon Lidofsky (Columbia University); Allen Sessoms (Dept. of State); Mary Shoaf (Princeton University); Irving Spiewak (Oak Ridge, Tennessee); Thomas Tombrello (California Institute of Technology).

Attached to this press release are copies of the executive summary and conclusions.

RADIONUCLIDE RELEASE FROM SEVERE ACCIDENTS AT NUCLEAR POWER PLANTS

EXECUTIVE SUMMARY

Report prepared by a study group of the American Physical Society under contract with the U.S. Nuclear Regulatory Commission

In 1983, the American Physical Society formed a study group on radionuclide release from severe accidents at nuclear power plants to "review the adequacy of the technical base upon which the phenomenological models for radionuclide release from postulated severe reactor accidents are constructed, the adequacy of the models themselves, and the correct use of the complex computer codes that incorporate these models in the analyses of accident sequences."

The impetus to the existing research came from the observation that much less radioactive iodine was released during the Three Mile Island accident than had been expected in an accident of that magnitude. It is of obvious interest to inquire how general that observation is.

Although this executive summary describes, explains, and paraphrases some of the conclusions of this report, any reference should be to the specific conclusion as written in Chapter VIII rather than to the executive summary.

This report is concerned with the release of radionuclides from a hypothetical severe nuclear reactor accident -- more severe than any that has yet taken place. It discusses both the predictions and the scientific basis for making them. Although we have not calculated probabilities of individual accident sequences, we have chosen for detailed discussion those sequences deemed by others to be "risk dominant" or to involve a wide range of physical and chemical phenomena.

The study group finds considerable progress in developing both a scientific basis and computational ability for predicting the consequences of hypothetical nuclear reactor accidents since the Reactor Safety Study of 1975 (WASH 1400) which is the current basis for regulation concerned with severe accidents. In several cases, the new calculations indicate that significantly smaller quantities of radionuclides reach the environment than calculated in the Reactor Safety Study. In other cases, the calculated quantities have not changed dramatically.

A reactor accident can lead to severe consequences only if several barriers between the radioactivity and the environment are breached. One postulated scenario by which this could occur is the failure of the core heat-removal systems. This would cause the core to overheat, lose coolant, melt, fall to the bottom of the reactor pressure vessel, melt through the vessel and be quenched in the water of the reactor cavity. This would release steam and non-condensible gases to the reactor containment building, and thereby increase the pressure, which

This report is concerned with the release of radionuclides from a hypothetical severe nuclear reactor accident -- more severe than any that has yet taken place. It discusses both the predictions and the scientific basis for making them. Although we have not calculated probabilities of individual accident sequences, we have chosen for detailed discussion those sequences deemed by others to be "risk dominant" or to involve a wide range of physical and chemical phenomena.

The study group finds considerable progress in developing both a scientific basis and computational ability for predicting the consequences of hypothetical nuclear reactor accidents since the Reactor Safety Study of 1975 (WASH 1400) which is the current basis for regulation concerned with severe accidents. In several cases, the new calculations indicate that significantly smaller quantities of radionuclides reach the environment than calculated in the Reactor Safety Study. In other cases, the calculated quantities have not changed dramatically.

A reactor accident can lead to severe consequences only if several barriers between the radioactivity and the environment are breached. One postulated scenario by which this could occur is the failure of the core heat-removal systems. This would cause the core to overheat, lose coolant, melt, fall to the bottom of the reactor pressure vessel, melt through the vessel and be quenched in the water of the reactor cavity. This would release steam and non-condensible gases to the reactor containment building, and thereby increase the pressure, which

would stress the containment. The Reactor Safety Study assigned a high probability -- one in ten -- that the containment would fail at this time. This is now considered to be very unlikely.

Once the water in the reactor cavity is evaporated, the core would remelt from the heat generated by the decay of the fission products and would attack the concrete floor. This interaction would be very complex, releasing gases and radioactive aerosols. Calculations indicate that this would cause the containment building to fail from overpressure many hours later -- although it is possible (and claimed by some investigators) that the containment would hold for many days. If the containment does not fail, the molten core might eventually penetrate the base-mat, but this possibility would have only modest immediate consequences for public safety.

Where new calculations indicate that radionuclide emissions would be less than those reported in the Reactor Safety Study, the reduction can be attributed to three principal factors:

(i) the recognition that the containment buildings, which are designed to contain the radionuclides in the event of an accident, are stronger than was assumed in the Reactor Safety Study and therefore would fail, if at all, at later times;

(ii) the inclusion in the modeling of various physical and chemical phenomena, previously neglected, that will lead to retention of fission products; this retention is particularly effective if more time elapses before containment failure; and

(iii) the inclusion in the calculation of a number of sites

which can retain fission products -- such as suppression pools and ice beds, and in some cases auxiliary buildings -- that had not previously been considered in detail.

The Reactor Safety Study pessimistically assumed that iodine would be released to the environment as gaseous molecular iodine. There is good evidence that the iodine reacts with cesium to form cesium iodide, a salt of low volatility, which would either dissolve in water or condense to form an aerosol. Some of the aerosols would deposit on surfaces in the primary reactor system or, if a sufficiently long time were available, on surfaces in the containment building; in either case, the release to the environment would be reduced.

Some reactors are equipped with suppression pools and ice condensers that are designed to condense steam. These can reduce the release by scavenging the fission products. However, experimental studies to evaluate their effectiveness are only now in progress (suppression pools) or have not been planned (ice beds). Moreover the effectiveness of these devices has not been subjected to detailed peer review. Reactors that contain these scavenging sites -- the Boiling Water Reactors with suppression pools and those few Pressurized Water Reactors with ice condenser containments -- have been studied far less than Pressurized Water Reactors with large dry containments, and little confirmatory work has been carried out. The study group recommends more study of hypothetical severe accidents involving these reactors.

The study group looked for phenomena which might increase the radionuclide releases above those calculated in the Reactor Safety Study. One such effect is the release of non-volatile radionuclides during the core-concrete interaction. Some non-volatile fission products, such as lanthanides, and some transuranics, such as plutonium, are biologically quite dangerous. The phenomena in the core-concrete interaction are complex and are not fully understood; releases depend critically upon the temperature achieved in the core-concrete interaction, and other parameters which are not understood. Moreover, the calculations are only in a preliminary stage. Some recent calculations indicate that releases of non-volatile species may be greater than predicted in the Reactor Safety Study for some postulated accident sequences. More experiments and analytical work are needed to improve the knowledge of the chemistry and physics in this crucial area.

Phenomena that could generate aerosols or volatile iodine late in an accident sequence as the result of decay heating or chemical reactions may also be underestimated. The aerosols or iodine might have very slow deposition rates, and even be emitted to the environment following a late containment failure. These phenomena are not included in the present NRC computer models.

The study group examined results produced by the computer codes used by participants in the severe accident research program. These codes have not, in general, been publicly released. Although these computer codes go a long way toward

describing the complex phenomena involved, and represent a major advance in the art of accident description, the normal scientific procedure for establishing the reliability of the results is not complete. The study group recommends that the theoretical and experimental studies be published in archival, peer-reviewed journals, and that the computer codes together with a clear and complete technical description of the models and the assumptions be made available to interested parties.

Reliable estimation of possible radionuclide release during severe accidents at nuclear power plants requires direct calculations, complex computer codes, small scale experiments, and large scale experiments. This research has been underway in several countries, some of the research being of an international cooperative nature. Because of the complexities of the phenomena being modeled, it is essential to compare the computer codes against well controlled, small scale experiments and against realistic, adequately instrumented, large scale integral experiments to insure that all important phenomena are modeled with sufficient accuracy. Such comparison is not yet completed. Because of this, the study group concluded that it cannot endorse at this time specific quantitative estimates for the amounts of radionuclides released. However, the general trends shown by the calculations are consistent with our understanding of the chemical and physical phenomena involved. Fortunately, some of the key parameters are largely determined by overall energy considerations (as for example the maximum pressure reached in the containment) and these can be estimated with a reasonable

degree of confidence.

The quantity of radionuclides released is called the source term. It consists of contributions from groups of radionuclides, broadly classified as gaseous, volatile, and non-volatile. The contributions from the first two of these have been widely considered to have the most significant potential impacts on public health. These are better understood now than they were previously.

The environmental impacts and mechanisms for releases of noble gases are the best understood. Their releases are not thought to differ importantly from those calculated in the Reactor Safety Study, except insofar as radioactive decay could reduce their radioactivity when containment failure is late. Some current calculations of the release of the volatile radionuclides to the environment predict substantially smaller values than those reported in the Reactor Safety Study because of the later times to containment failure. The magnitude of the contribution from the non-volatile radionuclides is still open to question, primarily because of the uncertainty of the core-concrete interaction.

For the reasons described in the previous six paragraphs, the study group believes that it is not yet possible to derive factors by which the source terms for all radionuclides and all reactors can be changed from the values reported in the Reactor Safety Study. Research that is currently in progress will

improve this situation and may enabl such factors to be determined for all important radionuclides and reactor sequences.

VIII. CONCLUSIONS AND RECOMMENDATIONS

VIII.A. Conclusions

VIII.A.1. The study group finds that considerable progress has been made since publication of the Reactor Safety Study (NRC 1975) in developing both a scientific basis and calculational ability for predicting the source term. In a number of cases, new calculations indicate that the quantity of radionuclides that would reach the environment is significantly lower than that calculated in the Reactor Safety Study. This reduction can be attributed to three principal factors: (i) the recognition that reactor containments are stronger than assumed in the Reactor Safety Study and therefore fail, if at all, at later times; (ii) inclusion in the modeling of previously neglected physical and chemical phenomena that lead to the retention of fission products; and (iii) inclusion of additional sites (suppression pools, ice beds, auxiliary buildings) that trap radionuclides more efficiently than previously assumed. These factors are discussed in more detail in Sections VIII.B.1 to VIII.B.8 below.

VIII.A.2. The study group examined the chemical and physical phenomena considered by the technical community since the Reactor Safety Study was completed. For most sequences and most radionuclides, these phenomena reduce the source term from that calculated in the Reactor Safety Study.

However, one mechanism that might, for some sequences,

increase the radionuclide releases above those calculated in the Reactor Safety Study is the release of non-volatile radionuclides in the core-concrete interaction. It is important to complete the experiments now underway to improve our knowledge of the physics and chemistry in this crucial area. Moreover, the analyses performed in the recent studies that we have surveyed have not treated all types of reactors nor all types of containments in equal detail. It is impossible to make the sweeping generalization that the calculated source term for any accident sequence involving any reactor plant would always be a small fraction of the fission product inventory at reactor shutdown. Although further studies may improve this situation, some of the reasons for this inability are enumerated in Sections VIII.C.1 to VIII.C.5 below.

VIII.B. Detail of Conclusion VIII.A.1

VIII.B.1. It is now generally believed that large scale failures of reactor containments will not occur until their yield stresses are exceeded -- at internal pressures about 2 1/2 times greater than the nominal design pressures. Some leakage may occur at lower pressures; in fact, earlier leakage could limit stresses to values below the yield stress. Quality assurance and testing programs are necessary to ensure that an individual containment achieves and retains the strength that is possible. The study group noted that such programs exist, but did not review them or their efficacy (see Section IV.D).

VIII.B.2. There are many accident sequences in the Reactor Safety Study in which large scale early failure was assumed. Detailed careful calculation of several risk dominant sequences, such as TMLB', suggest that such large early failures predicted for them do not occur if the containment is as strong as calculated. One reason for this is that accident-induced pressures within the containment are not expected to exceed yield stresses until many hours after the reactor pressure vessel failure. Another significant reason is that steam explosions large enough to challenge the containment directly are now considered very unlikely (see Sections IV.E.2 and III.C.1).

VIII.B.3. A delayed containment failure can allow time for natural, passive, mitigating processes to act. Several mechanisms operate that deposit aerosols onto surfaces both within the primary system and within the containment. To the extent that the Reactor Safety Study underestimated the time to failure and did not fully model these removal processes, the RSS over-estimated the "source terms" for the accident sequences (see Section III.C.1 and Section IV.D).

VIII.B.4. A delayed containment failure can also allow time for the plant operators, if they are adequately trained, to recover failed systems and to make effective use of active mitigating systems to achieve a safe shutdown (see Section III.C.1).

VIII.B.5. The source term for the release of noble gases, krypton and xenon, is better understood than any other source

term. Almost all of these radionuclides are released from the fuel; they are chemically inert, and are not affected by most of the retention mechanisms that reduce the importance of other radionuclides. On the other hand, they are not absorbed by the human body and do not deposit on the ground. Their releases are not believed to differ significantly from those calculated in the Reactor Safety Study, except insofar as radioactive decay reduces their radioactivity. If containment failure is delayed, the reduction is a factor of five between a two-hour release and a twenty-four-hour release (Section II.B).

VIII.B.6. The chemical form of some important fission products favors retention rather than release. Cesium hydroxide (CsOH), the dominant form of cesium that is observed in release from fuel irradiated in water cooled reactors, can interact chemically with surfaces in an irreversible way. Iodine is usually observed to take the form of cesium iodide (CsI) rather than molecular iodine (I_2), and CsI can deposit more readily than I_2 because CsI has a lower vapor pressure and higher solubility in water. In many sequences, tellurium tends to form non-volatile compounds with zirconium or stainless steel (see Section IV.B).

VIII.B.7. Fission products are calculated to be trapped, to a greater extent than was formerly assumed, in auxiliary buildings and related structures, suppression pools and ice condensers, even though these were not designed to remove fission products. The configuration of auxiliary buildings, and the penetrations from them to the containment are very plant specific. The ice

beds and suppression pools may remove large quantities of fission products. However, well designed, appropriate experiments are necessary to establish the effectiveness of removal under accident conditions. No experimental program has investigated the removal of fission products by ice condensers, and only recently has an appropriate program for suppression pools been started. The decontamination factors are expected to be sensitive to particle size and the relative humidity of the gases, as well as to other variables. Any credit taken for fission product removal by these devices must reflect the uncertainty in the knowledge of these controlling parameters (see Section IV.C).

VIII.B.8. The calculation of the source term when the containment has not been isolated or has been bypassed is very sensitive to the details of the failure . Accidents are more likely just before and just after maintenance periods, and this is just the time when isolation failure is also most likely. The containment bypass sequences (V) are specific for each reactor; once recognized, their probability and consequences can often be reduced by simple steps. We urge special attention to these potential problems by the designers and operators of nuclear installations (see Chapter VI).

VIII.B.9. The diversity of the various government, industrial and foreign groups engaged in source term research makes it unlikely that important phenomena will be left unconsidered. We urge these groups to continue to support the investigation of

source term phenomena until more of the areas of uncertainty are resolved (see Section VII.F).

VIII.C. Detail of Conclusion VIII.A.2

VIII.C.1. The selection of the accident sequences for the source term assessment is a very significant process. It is difficult to be sure that enough sequences have been studied to encompass all the physical phenomena involved. The study group believes that NRC and its contractors have selected the sequences reasonably well. However, several of these sequences no longer appear to be risk dominant, and other sequences have become relatively more important. In order to make sure that the risk dominant sequences have been adequately identified and investigated, we strongly urge another iteration of the process of selecting the sequences in the light of the understanding gained so far. Sequences that might be considered include containment isolation failure and containment bypass sequences, including the possibility of steam generator failure during a TMLB sequence externally initiated by an event such as an earthquake (see Section III.C).

VIII.C.2. Analyses of the Pressurized Water Reactors with large dry containments have been more extensive than those with ice condensers and of the Boiling Water Reactors. We urge that comparable attention be paid to these other reactor types.

VIII.C.3. If large amounts of the volatile elements cesium and

iodine were released, they would dominate the health hazard. For that reason, most of the studies to date have correctly concentrated on the magnitude of cesium, iodine, and to some extent, tellurium releases. However, if the calculations predict releases of cesium and iodine of less than a few percent of inventory, this by itself does not ensure a small source term. Considerable attention must then be paid to releases of the non-volatile elements (see Sections II.B and IV.B).

VIII.C.4. There is a tendency to accept the premise that a containment failure late in the accident will lead to small releases. However, some phenomena, not fully analyzed, might lead to higher releases than often calculated. These include the following:

a) Volatile fission products retained in the primary system might revaporize from decay heating at a time when there is less aerosol in the containment to scavenge these newly liberated species.

b) Deposited aerosols might be resuspended as a result of a sudden depressurization of the containment, or because of mechanical forces associated with steam explosions or hydrogen combustion.

c) The calculations for the core concrete interaction for some accident sequences suggest far larger releases of hazardous non-volatile radionuclides than were assumed in the Reactor

Safety Study. At this time it is neither clear that the physical and chemical phenomena involved have been correctly modeled nor clear that the calculations have been done correctly.

d) The deposition of the aerosols may not be as rapid as calculated, as a result of thermal stratification or lack of complete mixing.

e) The airborne concentrations of aerosols within the containment are sensitive to the time when condensed species are introduced. Conclusions must reflect the uncertainty in the mass release rates and aerosol characteristics (size, density and shape) of aerosols from both the primary system and the core concrete interaction (see Section IV.C).

VIII.C.5. Direct calculations, complex computer codes, small-scale experiments and large-scale experiments are all necessary to resolve the source-term questions. The relative role of these needs continual reevaluation. In particular, the large scale experiments such as BETA, DEMONA, MARVIKEN, PBF, by their nature, take a long time. It is important to continually reevaluate their experimental protocols to be sure that they provide data to validate the computer codes under conditions as close as possible to those occurring in reactor accidents (see Chapters V and VII).

VIII.D. <u>Possible Implications</u>

The Nuclear Regulatory Commission has used the methodology and conclusions of the Reactor Safety Study as the basis for emergency planning. The NRC has established an emergency planning zone of ten miles radius primarily on the premise that beyond ten miles few, if any, prompt deaths would occur in even the worst calculated accident. A fifty mile zone was established for considering health implications of contaminated food and drink.

Although recent calculations indicate that the source terms for several radioisotopes in a number of important sequences are smaller than the values obtained in the Reactor Safety Study, other considerations contribute to present regulations on emergency planning. Because these were not within its charter, the study group takes no position on the desirability of changes in those regulations.

The methodology of the Reactor Safety Study has also been used to evaluate proposed changes in reactor and nuclear plant design and operation -- either for future reactors or for retrofits to existing reactors -- to reduce the probability of accident. The study group has not studied the question of reducing the probability of accidents in detail and, therefore, merely notes the obvious general point that it is desirable to prevent accidents as early in the chain of events as possible -- for then the reactor may well stay intact in addition to the public being protected.

The insights gained from source term research and modeling should be reflected in the design and operation of light water reactor plants so as to minimize the source term -- and therefore the risk to the public -- in cost-effective ways.

VIII.E. Major Recommendations

The study group believes that the source term research cannot yet be regarded as adequate.

VIII.E.1. The NRC should continue to insure a strong, integrated, program of experimental and analytical studies in order to provide a sound data base for calculation of the source term.

VIII.E.2. The NRC should undertake uncertainty analyses so that calculated radionuclide releases can be stated within explicit limits.

VIII.E.3. The study group recommends that the theoretical and experimental studies be published in archival, peer-reviewed journals, and that the computer codes, together with a clear and complete technical description of the models and the assumptions, be made available to interested parties.

The American Physical Society

AMERICAN PHYSICAL SOCIETY STUDY GROUP ON RADIONUCLIDE RELEASE FROM SEVERE ACCIDENTS AT NUCLEAR POWER PLANTS

Please distribute the enclosed material to:

Mr. Palladino (Chairman)
Mr. Lando Zech, Jr. (Commissioner)
Mr. Frederick Bernthal (Commissioner)
Mr. James Asselstine (Commissioner)
Mr. Thomas Roberts (Commissioner)
— (Mr Chilk (Secretary to the Commission)
Mr William Dircks (Executive Director for Operations)

Thanks.

Diane Rolinski

Diane Rolinski

iLk 6 Seve Acad.

The American Physical Society

AMERICAN PHYSICAL SOCIETY STUDY GROUP ON RADIONUCLIDE RELEASE FROM SEVERE ACCIDENTS AT NUCLEAR POWER PLANTS

FOR INFORMATION: Contact F. Ingram
NRC 301-492-7715

FOR RELEASE: 21 February 1985

New calculations indicate that for many of the ways in which a severe nuclear reactor accident might occur (postulated accident scenarios or sequences) the quantity of radionuclides that would reach the environment (that is the "source term") is much lower than that predicted ten years ago in the earlier Reactor Safety Study (RSS) of 1975, often called the Rasmussen Report. This reduction is attributed to three principal factors:

1) The recognition that the reactor buildings are stronger than assumed by the RSS and therefore fail, if at all, at later times.

2) The inclusion in the modeling of previously ignored physical and chemical phenomena which lead to the retention of fission products.

3) The inclusion of additional sites which trap radionuclide releases more efficiently than previously assumed.

One mechanism that might, for some sequences, increase radionuclide release above those calculated in the Reactor Safety Study is the release of non-volatile radionuclides and the molten reactor core interactions with the concrete basemat.

Enc-IN 3P

G/10

RADIONUCLIDE RELEASE FROM SEVERE ACCIDENTS AT NUCLEAR POWER PLANTS

EXECUTIVE SUMMARY

Report prepared by a study group of the American Physical Society under contract with the U.S. Nuclear Regulatory Commission

In 1983, the American Physical Society formed a study group on radionuclide release from severe accidents at nuclear power plants to "review the adequacy of the technical base upon which the phenomenological models for radionuclide release from postulated severe reactor accidents are constructed, the adequacy of the models themselves, and the correct use of the complex computer codes that incorporate these models in the analyses of accident sequences."

The impetus to the existing research came from the observation that much less radioactive iodine was released during the Three Mile Island accident than had been expected in an accident of that magnitude. It is of obvious interest to inquire how general that observation is.

Although this executive summary describes, explains, and paraphrases some of the conclusions of this report, any reference should be to the specific conclusion as written in Chapter VIII rather than to the executive summary.

This report is concerned with the release of radionuclides from a hypothetical severe nuclear reactor accident -- more severe than any that has yet taken place. It discusses both the predictions and the scientific basis for making them. Although we have not calculated probabilities of individual accident sequences, we have chosen for detailed discussion those sequences deemed by others to be "risk dominant" or to involve a wide range of physical and chemical phenomena.

The study group finds considerable progress in developing both a scientific basis and computational ability for predicting the consequences of hypothetical nuclear reactor accidents since the Reactor Safety Study of 1975 (WASH 1400) which is the current basis for regulation concerned with severe accidents. In several cases, the new calculations indicate that significantly smaller quantities of radionuclides reach the environment than calculated in the Reactor Safety Study. In other cases, the calculated quantities have not changed dramatically.

A reactor accident can lead to severe consequences only if several barriers between the radioactivity and the environment are breached. One postulated scenario by which this could occur is the failure of the core heat-removal systems. This would cause the core to overheat, lose coolant, melt, fall to the bottom of the reactor pressure vessel, melt through the vessel and be quenched in the water of the reactor cavity. This would release steam and non-condensible gases to the reactor

containment building, and thereby increase the pressure, which would stress the containment. The Reactor Safety Study assigned a high probability -- one in ten -- that the containment would fail at this time. This is now considered to be very unlikely.

Once the water in the reactor cavity is evaporated, the core would remelt from the heat generated by the decay of the fission products and would attack the concrete floor. This interaction would be very complex, releasing gases and radioactive aerosols. Calculations indicate that this would cause the containment building to fail from overpressure many hours later -- although it is possible (and claimed by some investigators) that the containment would hold for many days. If the containment does not fail, the molten core might eventually penetrate the base-mat, but this possibility would have only modest immediate consequences for public safety.

Where new calculations indicate that radionuclide emissions would be less than those reported in the Reactor Safety Study, the reduction can be attributed to three principal factors:
(i) the recognition that the containment buildings, which are designed to contain the radionuclides in the event of an accident, are stronger than was assumed in the Reactor Safety Study and therefore would fail, if at all, at later times;
(ii) the inclusion in the modeling of various physical and chemical phenomena, previously neglected, that will lead to retention of fission products; this retention is particularly effective if more time elapses before containment failure; and
(iii) the inclusion in the calculation of a number of sites which can retain fission products -- such as suppression pools and ice beds, and in some cases auxiliary buildings -- that had not previously been considered in detail.

The Reactor Safety Study pessimistically assumed that iodine would be released to the environment as gaseous molecular iodine. There is good evidence that the iodine reacts with cesium to form cesium iodide, a salt of low volatility, which would either dissolve in water or condense to form an aerosol. Some of the aerosols would deposit on surfaces in the primary reactor system or, if a sufficiently long time were available, on surfaces in the containment building; in either case, the release to the environment would be reduced.

Some reactors are equipped with suppression pools and ice condensers that are designed to condense steam. These can reduce the release by scavenging the fission products. However, experimental studies to evaluate their effectiveness are only now in progress (suppression pools) or have not been planned (ice beds). Moreover the effectiveness of these devices has not been subjected to detailed peer review. Reactors that contain these scavenging sites -- the Boiling Water Reactors with suppression pools and those few Pressurized Water Reactors with ice condenser containments -- have been studied far less than Pressurized Water Reactors with large dry containments, and little confirmatory work has been carried out. The study group recommends more study

of hypothetical severe accidents involving these reactors.

The study group looked for phenomena which might <u>increase</u> the radionuclide releases above those calculated in the Reactor Safety Study. One such effect is the release of non-volatile radionuclides during the core-concrete interaction. Some non-volatile fission products, such as lanthanides, and some transuranics, such as plutonium, are biologically quite dangerous. The phenomena in the core-concrete interaction are complex and are not fully understood; releases depend critically upon the temperature achieved in the core-concrete interaction, and other parameters which are not understood. Moreover, the calculations are only in a preliminary stage. Some recent calculations indicate that releases of non-volatile species may be greater than predicted in the Reactor Safety Study for some postulated accident sequences. More experiments and analytical work are needed to improve the knowledge of the chemistry and physics in this crucial area.

Phenomena that could generate aerosols or volatile iodine late in an accident sequence as the result of decay heating or chemical reactions may also be underestimated. The aerosols or iodine might have very slow deposition rates, and even be emitted to the environment following a late containment failure. These phenomena are not included in the present NRC computer models.

The study group examined results produced by the computer codes used by participants in the severe accident research program. These codes have not, in general, been publicly released. Although these computer codes go a long way toward describing the complex phenomena involved, and represent a major advance in the art of accident description, the normal scientific procedure for establishing the reliability of the results is not complete. The study group recommends that the theoretical and experimental studies be published in archival, peer-reviewed journals, and that the computer codes together with a clear and complete technical description of the models and the assumptions be made available to interested parties.

Reliable estimation of possible radionuclide release during severe accidents at nuclear power plants requires direct calculations, complex computer codes, small scale experiments, and large scale experiments. This research has been underway in several countries, some of the research being of an international cooperative nature. Because of the complexities of the phenomena being modeled, it is essential to compare the computer codes against well controlled, small scale experiments and against realistic, adequately instrumented, large scale integral experiments to insure that all important phenomena are modeled with sufficient accuracy. Such comparison is not yet completed. Because of this, the study group concluded that it cannot endorse at this time specific quantitative estimates for the amounts of radionuclides released. However, the general trends shown by the calculations are consistent with our understanding of the chemical and physical phenomena involved. Fortunately, some of

the key parameters are largely determined by overall energy considerations (as for example the maximum pressure reached in the containment) and these can be estimated with a reasonable degree of confidence.

The quantity of radionuclides released is called the source term. It consists of contributions from groups of radionuclides, broadly classified as gaseous, volatile, and non-volatile. The contributions from the first two of these have been widely considered to have the most significant potential impacts on public health. These are better understood now than they were previously.

The environmental impacts and mechanisms for releases of noble gases are the best understood. Their releases are not thought to differ importantly from those calculated in the Reactor Safety Study, except insofar as radioactive decay could reduce their radioactivity when containment failure is late. Some current calculations of the release of the volatile radionuclides to the environment predict substantially smaller values than those reported in the Reactor Safety Study because of the later times to containment failure. The magnitude of the contribution from the non-volatile radionuclides is still open to question, primarily because of the uncertainty of the core-concrete interaction.

For the reasons described in the previous six paragraphs, the study group believes that it is not yet possible to derive factors by which the source terms for all radionuclides and all reactors can be changed from the values reported in the Reactor Safety Study. Research that is currently in progress will improve this situation and may enable such factors to be determined for all important radionuclides and reactor sequences.

VIII. CONCLUSIONS AND RECOMMENDATIONS

VIII.A. Conclusions

VIII.A.1. The study group finds that considerable progress has been made since publication of the Reactor Safety Study (NRC 1975) in developing both a scientific basis and calculational ability for predicting the source term. In a number of cases, new calculations indicate that the quantity of radionuclides that would reach the environment is significantly lower than that calculated in the Reactor Safety Study. This reduction can be attributed to three principal factors: (i) the recognition that reactor containments are stronger than assumed in the Reactor Safety Study and therefore fail, if at all, at later times; (ii) inclusion in the modeling of previously neglected physical and chemical phenomena that lead to the retention of fission products; and (iii) inclusion of additional sites (suppression pools, ice beds, auxiliary buildings) that trap radionuclides more efficiently than previously assumed. These factors are discussed in more detail in Sections VIII.B.1 to VIII.B.8 below.

VIII.A.2. The study group examined the chemical and physical phenomena considered by the technical community since the Reactor Safety Study was completed. For most sequences and most radionuclides, these phenomena reduce the source term from that calculated in the Reactor Safety Study.

However, one mechanism that might, for some sequences, increase the radionuclide releases above those calculated in the Reactor Safety Study is the release of non-volatile radionuclides in the core-concrete interaction. It is important to complete the experiments now underway to improve our knowledge of the physics and chemistry in this crucial area. Moreover, the analyses performed in the recent studies that we have surveyed have not treated all types of reactors nor all types of containments in equal detail. It is impossible to make the sweeping generalization that the calculated source term for any accident sequence involving any reactor plant would always be a small fraction of the fission product inventory at reactor shutdown. Although further studies may improve this situation, some of the reasons for this inability are enumerated in Sections VIII.C.1 to VIII.C.5 below.

VIII.B. Detail of Conclusion VIII.A.1

VIII.B.1. It is now generally believed that large scale failures of reactor containments will not occur until their yield stresses are exceeded -- at internal pressures about 2 1/2 times greater than the nominal design pressures. Some leakage may occur at lower pressures; in fact, earlier leakage could limit stresses to values below the yield stress. Quality assurance and testing programs are necessary to ensure that an individual containment achieves and retains the strength that is possible. The study group noted that such programs exist, but did not review them or their efficacy (see Section IV.D).

VIII.B.2. There are many accident sequences in the Reactor Safety Study in which large scale early failure was assumed. Detailed careful calculation of several risk dominant sequences, such as TMLB', suggest that such large early failures predicted for them do not occur if the containment is as strong as calculated. One reason for this is that accident-induced pressures within the containment are not expected to exceed yield stresses until many hours after the reactor pressure vessel failure. Another significant reason is that steam explosions large enough to challenge the containment directly are now considered very unlikely (see Sections IV.E.2 and III.C.1).

VIII.B.3. A delayed containment failure can allow time for natural, passive, mitigating processes to act. Several mechanisms operate that deposit aerosols onto surfaces both within the primary system and within the containment. To the extent that the Reactor Safety Study underestimated the time to failure and did not fully model these removal processes, the RSS over-estimated the "source terms" for the accident sequences (see Section III.C.1 and Section IV.D).

VIII.B.4. A delayed containment failure can also allow time for the plant operators, if they are adequately trained, to recover failed systems and to make effective use of active mitigating systems to achieve a safe shutdown (see Section III.C.1).

VIII.B.5. The source term for the release of noble gases, krypton and xenon, is better understood than any other source term. Almost all of these radionuclides are released from the fuel; they are chemically inert, and are not affected by most of the retention mechanisms that reduce the importance of other radionuclides. On the other hand, they are not absorbed by the human body and do not deposit on the ground. Their releases are not believed to differ significantly from those calculated in the Reactor Safety Study, except insofar as radioactive decay reduces their radioactivity. If containment failure is delayed, the reduction is a factor of five between a two-hour release and a twenty-four-hour release (Section II.B).

VIII.B.6. The chemical form of some important fission products favors retention rather than release. Cesium hydroxide (CsOH), the dominant form of cesium that is observed in release from fuel irradiated in water cooled reactors, can interact chemically with surfaces in an irreversible way. Iodine is usually observed to take the form of cesium iodide (CsI) rather than molecular iodine (I_2), and CsI can deposit more readily than I_2 because CsI has a lower vapor pressure and higher solubility in water. In many sequences, tellurium tends to form non-volatile compounds with zirconium or stainless steel (see Section IV.B).

VIII.B.7. Fission products are calculated to be trapped, to a greater extent than was formerly assumed, in auxiliary buildings and related structures, suppression pools and ice condensers, even though these were not designed to remove fission products.

The configuration of auxiliary buildings, and the penetrations from them to the containment are very plant specific. The ice beds and suppression pools may remove large quantities of fission products. However, well designed, appropriate experiments are necessary to establish the effectiveness of removal under accident conditions. No experimental program has invertigated the removal of fission products by ice condensers, and only recently has an appropriate program for suppression pools been started. The decontamination factors are expected to be sensitive to particle size and the relative humidity of the gases, as well as to other variables. Any credit taken for fission product removal by these devices must reflect the uncertainty in the knowledge of these controlling parameters (see Section IV.C).

VIII.B.8. The calculation of the source term when the containment has not been isolated or has been bypassed is very sensitive to the details of the failure . Accidents are more likely just before and just after maintenance periods, and this is just the time when isolation failure is also most likely. The containment bypass sequences (V) are specific for each reactor; once recognized, their probability and consequences can often be reduced by simple steps. We urge special attention to these potential problems by the designers and operators of nuclear installations (see Chapter VI).

VIII.B.9. The diversity of the various government, industrial and foreign groups engaged in source term research makes it unlikely that important phenomena will be left unconsidered. We urge these groups to continue to support the investigation of source term phenomena until more of the areas of uncertainty are resolved (see Section VII.F).

VIII.C. <u>Detail of Conclusion VIII.A.2</u>

VIII.C.1. The selection of the accident sequences for the source term assessment is a very significant process. It is difficult to be sure that enough sequences have been studied to encompass all the physical phenomena involved. The study group believes that NRC and its contractors have selected the sequences reasonably well. However, several of these sequences no longer appear to be risk dominant, and other sequences have become relatively more important. In order to make sure that the risk dominant sequences have been adequately identified and investigated, we strongly urge another iteration of the process of selecting the sequences in the light of the understanding gained so far. Sequences that might be considered include containment isolation failure and containment bypass sequences, including the possibility of steam generator failure during a TMLB sequence externally initiated by an event such as an earthquake, fire or flood (see Section III.C).

VIII.C.2. Analyses of the Pressurized Water Reactors with large dry containments have been more extensive than those with ice condensers and of the Boiling Water Reactors. We urge that

comparable attention be paid to these other reactor types.

VIII.C.3. If large amounts of the volatile elements cesium and iodine were released, they would dominate the health hazard. For that reason, most of the studies to date have correctly concentrated on the magnitude of cesium, iodine, and to some extent, tellurium releases. However, if the calculations predict releases of cesium and iodine of less than a few percent of inventory, this by itself does not ensure a small source term. Considerable attention must then be paid to releases of the non-volatile elements (see Sections II.B and IV.B).

VIII.C.4. There is a tendency to accept the premise that a containment failure late in the accident will lead to small releases. However, some phenomena, not fully analyzed, might lead to higher releases than often calculated. These include the following:

a) Volatile fission products retained in the primary system might revaporize from decay heating at a time when there is less aerosol in the containment to scavenge these newly liberated species.

b) Deposited aerosols might be resuspended as a result of a sudden depressurization of the containment, or because of mechanical forces associated with steam explosions or hydrogen combustion.

c) The calculations for the core concrete interaction for some accident sequences suggest far larger releases of hazardous non-volatile radionuclides than were assumed in the Reactor Safety Study. At this time it is neither clear that the physical and chemical phenomena involved have been correctly modeled nor clear that the calculations have been done correctly.

d) The deposition of the aerosols may not be as rapid as calculated, as a result of thermal stratification or lack of complete mixing.

e) The airborne concentrations of aerosols within the containment are sensitive to the time when condensed species are introduced. Conclusions must reflect the uncertainty in the mass release rates and aerosol characteristics (size, density and shape) of aerosols from both the primary system and the core concrete interaction (see Section IV.C).

III.C.5. Direct calculations, complex computer codes, small-scale experiments and large-scale experiments are all necessary to resolve the source-term questions. The relative role of these needs continual reevaluation. In particular, the large scale experiments such as BETA, DEMONA, MARVIKEN, PBF, by their nature take a long time. It is important to continually reevaluate their experimental protocols to be sure that they

provide data to validate the computer codes under conditions as close as possible to those occurring in reactor accidents (see Chapters V and VII).

VIII.D. Possible Implications

The Nuclear Regulatory Commission has used the methodology and conclusions of the Reactor Safety Study as the basis for emergency planning. The NRC has established an emergency planning zone of ten miles radius primarily on the premise that beyond ten miles few, if any, prompt deaths would occur in even the worst calculated accident. A fifty mile zone was established for considering health implications of contaminated food and drink.

Although recent calculations indicate that the source terms for several radioisotopes in a number of important sequences are smaller than the values obtained in the Reactor Safety Study, other considerations contribute to present regulations on emergency planning. Because these were not within its charter, the study group takes no position on the desirability of changes in those regulations.

The methodology of the Reactor Safety Study has also been used to evaluate proposed changes in reactor and nuclear plant design and operation -- either for future reactors or for retrofits to existing reactors -- to reduce the probability of accident. The study group has not studied the question of reducing the probability of accidents in detail and, therefore, merely notes the obvious general point that it is desirable to prevent accidents as early in the chain of events as possible -- for then the reactor may well stay intact in addition to the public being protected.

The insights gained from source term research and modeling should be reflected in the design and operation of light water reactor plants so as to minimize the source term -- and therefore the risk to the public -- in cost-effective ways.

VIII.E. Major Recommendations

The study group believes that the source term research cannot yet be regarded as adequate.

VIII.E.1. The NRC should continue to insure a strong, integrated, program of experimental and analytical studies in order to provide a sound data base for calculation of the source term.

VIII.E.2. The NRC should undertake uncertainty analyses so that calculated radionuclide releases can be stated within explicit limits.

VIII.E.3. The study group recommends that the theoretical and experimental studies be published in archival, peer-reviewed

journals, and that the computer codes, together with a clear and complete technical description of the models and the assumptions, be made available to interested parties.