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INTERNATIONAL NUCLEAR SAFETY ADVISORY GROUP

Radionuclide Source Terms from Severe Accidents to Nuclear Power Plants with Light Water Reactors

INTERNATIONAL ATOMIC ENERGY AGENCY, VIENNA, 1987

RADIONUCLIDE SOURCE TERMS FROM SEVERE ACCIDENTS TO NUCLEAR POWER PLANTS WITH LIGHT WATER REACTORS

Report by the International Nuclear Safety Advisory Group

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FOREWORD
by the Director General

The International Atomic Energy Agency's activities related to nuclear safety are based upon a number of premises. First and foremost, each Member State carries full responsibility for the safety of its nuclear facilities. States can only be advised, not relieved of this responsibility. Secondly, much can be gained by exchanging experience worldwide; lessons learned can prevent serious accidents. Finally, the image of nuclear safety is international; an accident anywhere affects the public's view of nuclear power everywhere.

With the intention of strengthening the Agency's contribution to ensuring the safety of nuclear power plants, I established the International Nuclear Safety Advisory Group (INSAG) to serve as a forum for the exchange of information on nuclear safety issues of international significance. INSAG seeks not only to identify such issues, but also to draw conclusions on the basis of worldwide nuclear safety research and operational experience. It advises on areas where exchanges of information and additional efforts are required. Where possible, it intends to formulate common safety concepts.

INSAG began its activities in March 1985. As its first significant contribution, it directed and prepared the official Agency report on the Post-Accident Review Meeting held in Vienna in August 1986 to review the accident at the Chernobyl nuclear power plant in the USSR in April 1986 (International Atomic Energy Agency, Summary Report on the Post-Accident Review Meeting on the Chernobyl Accident, Safety Series No. 75-INSAG-1, IAEA, Vienna (1986)). The present report was in preparation when the Chernobyl accident occurred, and its publication was deferred because of the need to concentrate on reactions to the event. INSAG is now issuing this report on the fission product source term that might result from a severe accident to a light water reactor of the pressurized water reactor or boiling water reactor type. An appendix has been added to reflect the relevance of information available on the fission product release at the Chernobyl power plant site.

I am pleased to have received this report and am happy to release it to a wider audience.

PREFACE
by the Chairman of INSAG

The International Nuclear Safety Advisory Group (INSAG) is an advisory group to the Director General of the International Atomic Energy Agency, the main functions of which are:

(1) To provide a forum for the exchange of information on generic nuclear safety issues of international significance;
(2) To identify important current nuclear safety issues and to draw conclusions on the basis of the results of nuclear safety activities within the IAEA and of other information;
(3) To give advice on nuclear safety issues in which an exchange of information and additional efforts may be required;
(4) To formulate, where possible, commonly shared safety concepts.

The nuclear safety issues which have been of major concern have changed with time, but most have been related to the expected effects of severe accidents on the health and safety of people living in the vicinity of nuclear power plants.

At its first meeting, INSAG identified the issue of the source term for the release of fission products from severe accidents to nuclear power plants with light water reactors (LWRs) as one on which it should draw conclusions.

The main reasons for giving priority to this issue were the following:

- if a severe accident occurred, the consequences could be very serious;
- a considerable amount of experimental evidence is available from many research organizations and many technical reports on the issue;
- there is a potential for improving safety in this area;
- there is an opportunity to improve the general understanding of the risks arising from the use of nuclear power, and for obtaining a better perspective on nuclear safety; and
- LWRs constitute the overwhelming majority of nuclear power plants in the world.

In this report, INSAG presents its views on the source term issue for LWRs of existing designs. These views are based in part on experience and a considerable amount of judgement and are not in the form of a detailed technical paper. The report notes conclusions which are already widely accepted by the nuclear community; suggests additional conclusions which INSAG believes can be drawn; identifies problems which remain to be resolved; and indicates areas where work should be initiated to improve safety.

It is probable that future research and operational experience will yield information which will deepen the understanding of this issue and reduce uncertainties, thus improving confidence in the adequacy of our knowledge of the source term to meet requirements for the assurance of safety, not only of LWRs, but of all nuclear systems.

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RADIONUCLIDE SOURCE TERMS FROM SEVERE ACCIDENTS TO NUCLEAR POWER PLANTS WITH LIGHT WATER REACTORS

Report by the International Nuclear Safety Advisory Group

Introduction

Nuclear power plants[1] of the light water reactor (LWR) type are so designed and operated that no accident reasonably considered to be possible would release significant amounts of fission products to the environment. It follows that rare improbable events such as severe accidents would provide the only potentially significant contribution to adverse human health effects. The potential for such severe nuclear power plant accidents beyond the design basis of an LWR has received a great deal of scrutiny since the accident at Three Mile Island in the United States of America in 1979. This report considers only such severe accidents.

A severe accident to an LWR nuclear power plant could in principle release substantial amounts of fission products to the environment. It has always been recognized as important that the possibility of such a release should be made small in the scale of normal human concerns. The highest priority is the prevention of any severe accident which would lead to extensive fuel failure. It is nonetheless important to recognize that such severe accidents are not impossible, and that their probability of occurrence may be higher, or lower, than currently thought. It is for this reason that these reactors are provided with strong containments and other engineered features to mitigate the effects of severe accidents.

Quantitative estimation of the amount of fission products that might be released — the source term — obviously continues to be of value. This estimate is needed as part of the analysis of the effectiveness of such measures as design features and accident management[2] to prevent the release, and it is also needed for planning accident management in case such an event does occur. Research and analysis on LWR source term questions are being performed in several IAEA Member States.

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[1] This report has been prepared to be pertinent to nuclear power plants with reactors cooled and moderated by light water, of types for which risk assessments have been published and discussed in the scientific community and with strong containments capable of withstanding the effects of accidents. This includes both pressurized water reactors (PWRs) and boiling water reactors (BWRs) of existing designs.

[2] 'Accident management' refers to the totality of measures, both short term and long term, taken to control the course of an accident in progress and to mitigate the consequences of an accident during its occurrence. Examples of measures that may be involved are procedures, communications, analyses, ad hoc plans, the use of outside specialist help, special equipment, etc.

In this report, INSAG considers the present status of source term research and analysis, and presents its current views on the implications. This report is not a scientific paper but an expression of the engineering judgement of INSAG members.

A report on the implications of the current state of source term technology has been prepared by the IAEA[3], and this is drawn on to some extent in the present report. INSAG has also considered documents furnished by the Committee on the Safety of Nuclear Installations of the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development[4].

The present report is based primarily on a technical review of severe accidents affecting LWRs, which are certain reactors cooled and moderated by light water, of types for which risk assessments have been published and discussed by the scientific community, and with strong protective containment structures. It does not consider safety issues for severe accidents to the several other types of nuclear power plants now in commercial operation, nor to those types of nuclear plants still under development. It is considered that each of these systems is different from the LWR to the extent that their overall safety must be considered on a separate basis. INSAG has made no judgement on the relative safety of these other types of nuclear power plants.

INSAG has reviewed the accident at the Chernobyl nuclear power plant in the USSR in April 1986. On the basis of the information presently available, it is the opinion of INSAG that this event has no implications for the conclusions given in this report.

Purpose

It is the intent here to summarize the state of understanding of the source term question as it affects overall estimates of risk to the public from the operation of LWRs, and to draw some conclusions.

Probabilistic safety analysis

The source term from an LWR as an isolated issue attracted considerable attention as a result of the minimal release of fission products to the environment during the accident to the Three Mile Island (TMI) nuclear power plant. It was tempting

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[3] INTERNATIONAL ATOMIC ENERGY AGENCY, The Practical Implications of Source Term Reassessment Studies (in final preparation).

[4] NUCLEAR ENERGY AGENCY OF THE ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT, Draft report of Senior Group of Experts on Severe Accidents (October 1985); draft report of Working Group on Source Term and Environmental Consequences (October 1985), OECD/NEA, Paris.

at that time to generalize this observation of low release to conclude that the amount of fission products that might be released after any accident to these plants would be substantially less than had been calculated in the WASH-1400 Reactor Safety Study (see Bibliography) and later studies. Subsequent analysis and experimental research do not support this generalization. However, the fact that the TMI accident led to core damage beyond that calculated for design basis events emphasized the need for a careful review of the potential consequences of accidents beyond the design basis.

The source term question is now viewed as only one part of the 'consequence analysis' in the probabilistic safety analysis of a nuclear plant. It is now realized that the source term itself is very dependent on plant design and the performance of the containment. Consideration of accident sequences requires that both their probability of occurrence and their consequences be taken into account. Any sequence which has a combination of source term and probability leading to an important contribution *to risk*[5] *is an important sequence. With regard to risk, this is the definition of* importance.

Recognition of this has important implications. If a phenomenon in an accident sequence does not appreciably affect the overall estimate of risk to the public, that phenomenon becomes relatively unimportant in this regard. Also, a phenomenon or practice that decreases risk is just as important whatever way it reduces risk. Thus, measures that reduce risk by reducing the probability of core melt are, from this point of view, as important as measures that reduce the source term. From other standpoints one would say that preventing core melt in the first place is much more desirable.

Obviously, if it is easy to take measures, such as planned operator action, that would prevent or mitigate accidents with a high source term but low risk contribution, it would be worthwhile to do so.

General issues

In the following, we consider the current points of view in the technical community on four questions. These are:

(1) What technically possible scenarios may lead to a high contribution to risk through the magnitude of the source term?

(2) How well are the phenomena understood and modelled?

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[5] Risk is defined as the probability of occurrence of a postulated sequence multiplied by its off-site consequences; the process of estimating the risk for a plant includes identification of all accident sequences and their frequencies, possible containment failure modes (or continued containment integrity), calculation of source terms, calculation of off-site consequences for each of the source terms, and calculation of an estimate of risk. The set of risk estimates that covers all the dominant sequences would provide a risk estimate for a plant.

(3) How can scenarios involving these possibilities be prevented from occurring?
(4) How should such scenarios be responded to if they did occur?

The technical community is not yet unanimous in its views on these issues, but areas of agreement are growing steadily.

High source term sequences

The reactor accidents that could in principle have the largest source term for a given LWR plant are those in which severe fuel damage occurs in addition to one of three classes of containment impairment. The accidents are those that: (1) might threaten containment integrity early in the history of the event; (2) might remobilize large amounts of fission products in late containment failure; and (3) might lead to bypass of the containment function.

Even as early as the Reactor Safety Study report WASH-1400 of the USNRC (see Bibliograpy) it was concluded that basemat melt-through could not lead to high source terms for an LWR.

Early containment failure

The phenomena that have been considered as possible causes of early containment failure are steam explosions in the reactor vessel, burning or detonation of hydrogen generated during an accident, and containment overpressure from steam and direct heating of the containment atmosphere. Some accident sequences that could threaten the containment, such as those involving failure of the pressure vessel, are considered to have so low a probability that their contribution to risk can be neglected.

It is now generally believed that steam explosions could occur in the reactor vessel if a molten core fell into residual water below. However, it is also generally accepted that the explosion could only be large enough to endanger the containment if most of the core fell coherently as a molten mass into the water under restricted conditions of geometry. The probability of this combination of circumstances is commonly considered to be so low that this contribution to risk may be ignored, as can the associated source term.

The threat due to hydrogen deflagration or detonation is met in two ways. The first is through new analysis that takes into account the actual strength of containment structures. It is found that in a great many cases the reactor containment is already strong enough to withstand pressures generated by hydrogen burning. In some cases, where this might be questionable, additional measures such as pre-inerting or the use of igniters have been implemented. Analysis of certain effects of hydrogen is continuing. However, precautions have been taken where analysis indicates that they are needed, and containment failure due to hydrogen deflagration and detonation is now commonly considered to have a low probability.

There are other conceivable sources of overpressure apart from that which might result from burning of hydrogen. One is the steam pressure 'spike' that might be generated if a molten reactor core fell into water on the reactor building floor after it had melted its way through the reactor vessel. Another possibility for some plant designs would be direct heating of the containment atmosphere by molten core material, at approximately the same time in the history of the accident. Both effects and even combinations of them are being analysed further, particularly direct heating scenarios. The importance of further studies in this area can hardly be overemphasized. However, INSAG considers that it will be found that the probability of such effects is too low for them to contribute appreciably to risk.

Suppression pool bypass, with a resultant possibility of early containment failure, might be a non-negligible contributor to risk for some boiling water reactors.

Remobilization of fission products

If an accident were to lead to core melting in the reactor vessel, fission products would be generated as gases and aerosols. Some of the fission products evolved would be deposited in the primary system. It is now considered that subsequently, as the temperatures of the walls and components of the primary system increase, these fission products would to some extent re-evolve and escape the primary system. Their contributions to the source term would depend on the timing of the containment failure.

Deposition in the containment would also occur after the molten core had melted its way into the containment. After some time, aerosols would agglomerate and settle on surfaces. Containment failure would lead to a sudden decrease of pressure that could remobilize some deposited aerosols. These airborne aerosols could then leak out from within the containment. Some would be retained in surrounding structures.

The extent of re-evolution of fission products from the plant is commonly considered to be not large, but it is recognized as contributing to the source term for late containment failure.

Bypass of containment

The simplest example of bypass of the containment would be leakage through a penetration that had not been properly sealed. This could result, for example, from the failed closure of an isolation valve in a ventilation system.

Another mode of containment bypass that is sometimes overlooked is failure of steam generator tubes caused by loads imposed by forces during a severe accident.

The WASH-1400 Reactor Safety Study also pointed out the importance of the interfacing systems loss of coolant accidents (LOCAs) (Event V), which would be the result of failure of the isolation valves separating the high pressure primary system from a low pressure injection component of the emergency core cooling system.

A simple system modification is used to reduce the probability of Event V for a PWR to an adequately low value. This consists of monitoring the pressure between the two check valves in the line connecting the low pressure injection system to the high pressure primary system. Recent analysis has also indicated the importance of design; for example, in an interfacing systems LOCA any release of fission products might be under water, with mitigating effects similar to those in the Three Mile Island accident.

However, the possibility that human failure or isolation valve failure would compromise containment seems to set a limit to containment effectiveness for any nuclear plant requiring active isolation in the event of an accident.

In the analysis of the source term from containment bypass, important reductions may be attributable to surrounding structures through which containment leakage must pass.

Other issues

As stated earlier, some questions associated with the possibilities of early containment failure are still being explored in some places. A few of the other aspects of risk related to the source term that are still being reviewed are discussed in what follows. Although most of these may have only a small effect on risk, these contributions have large uncertainties, and it is important that research be continued to answer outstanding questions.

Physical and chemical phenomena that occur in interactions of molten corium with concrete have been vigorously studied over the past few years. Some phenomena are well understood, but others are still in question. The difference between results with limestone and basaltic concretes is now well appreciated; the interaction of molten corium with the former leads to the generation of appreciably more aerosols than that with the latter. Some information is still lacking about the chemical composition of the aerosol from limestone, and the beneficial effects of non-active aerosols in enhancing agglomeration and settling have still not been evaluated. More importantly, there is contradictory information on the effect of aerosols from core-concrete interactions in transferring non-volatile fission products into the aerosol.

Questions have recently been raised concerning the radiation stability of chemical compounds involving fission products. In particular, some experiments indicate that in a high radiation field CsI may decompose into its elemental constituents, and as a result iodine may be liberated, in elemental form or as methyl iodide, in greater amounts than have previously been thought possible. This is a question that should easily yield to a careful experimental programme, and we urge that this research be carried out.

A number of questions concerning fission product chemistry remain to be settled, such as the reactions with surfaces that the released fission products might encounter in a containment building.

Questions have been raised, especially concerning boiling water reactors, about the fraction of zirconium clad and structure that would be oxidized in-vessel during an accident, and the fraction that would remain to be oxidized later, such as during a core–concrete interaction after release from the reactor vessel. If very much zirconium remained unoxidized on leaving the reactor vessel, the heat generated by chemical reactions during the core–concrete interaction could exceed the rate of heat production from fission product decay. This would strongly affect the course of the core–concrete interaction.

Some recent experiments with irradiated fuel appear to indicate that more transuranic isotopes could be released from high temperature fuel than has previously been thought possible.

Such uncertainties are typical of those which appear at the leading edge of any developing technology. It is expected that research will continue for some years. However, given the extensive investigations which have already been made in the field of reactor safety, it is unlikely that major new issues of real significance for public safety will arise from these studies. The main purpose of the remaining research is better to quantify issues that are presently recognized.

Reduction of risk and source term through accident prevention, management and mitigation

In a sense, the reduction of the source term and of risk through design has been an inherent part of LWR nuclear plant design from the outset. All engineered safety features are directed to this end. Certain design changes that have been made in recent years have been aimed at reducing the source term if severe core damage occurred. Examples are the igniters in some plants in the USA, and the filtered, vented release systems of French and Swedish plants, now also being introduced in the Federal Republic of Germany.

One of the most important recent developments has been the move to reduce risk and the source term through accident management. This involves analysis of the event trees of accidents to determine what special measures could be taken to make use of the normal plant systems to prevent core melt even if there were failure of all engineered safeguards, or to reduce the magnitude of the source term in other ways. One example is the use of unusual cooling systems (e.g. charging pumps or control rod cooling pumps) to maintain core cooling in the event of loss of all feedwater.

It is necessary that these measures be suitably analysed, that the symptoms indicating them be suitably identified so that an operator in the control room can recognize when the measures are needed, and that procedures for the mitigating action be made part of the operating instructions with which the operating staff has been made familiar. These actions can then be taken into account in risk analysis and in other assessments.

Important advances are being made in control room design and layout and in the use of computers in information processing and analysis for diagnosis and control of abnormal occurrences.

Active development of accident management measures by plant personnel can lead to very large reductions in source terms and risk. This course of action is being followed in several IAEA Member States.

Accurate understanding of the potential source terms for accidents, together with good information on the state of plant systems after an accident, are necessary for the intelligent and effective use of any mitigating measures. For instance, LWR source term studies now show that some period of time would be available after an accident began before any release of fission products to the environment could occur. This interval of time could be used for taking appropriate decisions concerning accident management and measures to mitigate the effect of any possible release.

Apart from accident management of the kind already referred to, there are other modes of response to accidents, if they should occur, that can reduce risk. One example is the sheltering and/or evacuation of surrounding populations if a major release of radioactivity to the environment appears imminent.

In summary, there are two ways of coping with the issue of severe accidents in LWR plants, and they should be treated separately from a regulatory point of view. The first is by designing the plant, and all engineered safety features, with the main objective of prevention; the second is throught accident management.

Conclusions

(1) On careful review of the status of understanding of the source term for severe accidents to LWRs, and the associated implications for risk, we find no need for new immediate generic corrective action to improve the safety of existing LWR nuclear power plants. The evidence remains strong that nuclear plants are a safe means of generating electricity.

(2) The most important ways to maintain risk and the source term at low levels are design features and accident management methods that would prevent severe core damage. The next most important are design features and accident management methods that would preserve the integrity and the functions of the containment. Design features and other measures to reduce the extent of fission product release or to mitigate the effects of release are also important, but these

would not be needed if either or both of the reactor core cooling and the containment function were preserved.

(3) The degree of safety of a given individual plant depends strongly on details of its design, construction, maintenance and operating practice. Many technical measures have been taken in the past to reduce the probability of severe accidents to LWRs, especially through design. Measures have also been taken to reduce the risk from severe accidents if they should occur. The most fruitful path to follow in reducing risk even further is through the planning of accident management. It is considered that if this is done well, the risks associated with nuclear power could be further reduced by a substantial factor, at relatively small expense.

(4) Sets of analytical tools have been developed to model physical behaviour and plant phenomena under severe accident conditions. These codes model all phenomena now considered to be important. We believe that no new phenomenon or feature relating to LWR source terms will be found that could substantially change present estimates of risk. However, it is realized that severe accident analysis calls for physical information and a description of the behaviour of materials under extreme conditions, for which the engineering database is poor. As a result, severe accident analysis will always be less certain than design basis accident analysis. There will always be questions that have not been settled as well as could be desired. Research should continue to resolve questions of safety significance on which engineering judgement needs further reinforcing by a sounder physical understanding.

(5) Effort should be increased to engage and train the management and operating staff of LWR nuclear plants in ways of dealing with abnormal events and in the evaluation of severe accident sequences, as well as in accident management. In this way, utility management would not only improve its protection of the public, but would also improve the protection of its investment.

(6) Realistic reviews lead to the conclusion that LWR accident scenarios involving melt-through of the basemat would be associated with low values of the source term and risk.

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Appendix

IMPLICATIONS OF THE SOURCE TERM FROM THE CHERNOBYL ACCIDENT

In its report on the Chernobyl accident (see Bibliography), INSAG noted (pp. 33–42) that the timing and duration of the release processes during this accident were unusual in comparison with expectations based on severe accident analyses made for reactors of other types. Furthermore, the isotopic content and character of the materials released did not conform closely to those found in previous accident analyses.

Some features of the source term for the Chernobyl accident would be expected to be found also in more extreme scenarios of release of fission products after a severe accident to an LWR:

(1) Release of noble gases from failed fuel is believed to have been almost complete (100%).
(2) Volatile but chemically active species (I, Cs, Te) were released from fuel to a greater extent than non-volatile species.

The dissimilarities from source terms commonly attributed to hypothetical LWR accidents are more striking than the similarities. They include the following observations:

(1) There was a very large release at the time of the destruction of the Chernobyl reactor, caused by failure of those containment features that were present. It is reasonable to believe that essentially all the noble gas release and a large fraction of the volatile release took place at that time.
(2) The non-volatile elements were released in almost the same relative fractions as in the fuel before the accident. About 3% to 5% of all those initially present were released. Most of the release of non-volatile fission products took place in the ejection of fuel by the initial event.
(3) The subsequent release took place over a period of many days. The release rate on the ninth day exceeded that on any other day, except for the violent release at the start of the accident.
(4) The release rate of fission products fell dramatically between the ninth and the tenth day of the accident.

Though the exact causes of all these features have not yet been established beyond question, the composition of the release is consistent with the Soviet supposition[6] that, at the time of the destruction of the fuel, the uranium oxide and the fission products and actinides it contained were ejected into the water as a fine powder, leading to a steam pressure 'spike' that was the cause of the destruction of the reactor. It is also consistent with the view of the Soviet experts that subsequent general melting of the fuel did not occur. Presumably, fuel temperatures were kept low by the large heat transfer surface of the finely divided fuel, and by the flow of air through the opened reactor space. Subsequent release after the initial destruction of the reactor would then consist largely of an aerosol of the finely divided fuel particles, lofted by the flow of air and graphite combustion gases, perhaps altered in composition and form by the graphite fire and other chemical effects. During most of the period of release, the heat due to the burning of graphite was comparable to, if not greater than, the heat due to fission product decay.

It may also be assumed (though not incontrovertibly) that the fission product release continued at a high rate as long as the graphite fire smouldered.

The nature of the fission product release from the Chernobyl reactor was intimately related to specific features of the Chernobyl plant design which are not present in LWR designs.

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[6] USSR STATE COMMITTEE ON THE UTILIZATION OF ATOMIC ENERGY, The Accident at the Chernobyl Nuclear Power Plant and its Consequences (Information compiled for the IAEA Experts Meeting, Vienna, 25–29 August 1986), Part I, General Material, August 1986.

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