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A COMPARISON OF WORLD-WIDE USES OF SEVERE REACTOR ACCIDENT SOURCE TERMS

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ABSTRACT

The definitions of source terms to reactor containments and source terms to the environment are discussed. A comparison is made between the TID-14844 example source term and the alternative source term described in NUREG-1465. Comparisons of these source terms to the containments and those used in France, Germany, Japan, Sweden, and the United Kingdom are made. Source terms to the environment calculated in NUREG-1500 and WASH-1400 are discussed. Again, these source terms are compared to those now being used in France, Germany, Japan, Sweden, and the United Kingdom.

It is concluded that source terms to the containment suggested in NUREG-1465 are not greatly more conservative than those used in other countries. Technical bases for the source terms are similar. The regulatory use of the current understanding of radionuclide behavior varies among countries.

DISCLAIMER

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TABLES

I. Background

Regulatory and public concerns about the use of nuclear reactors for power production focus on the potential for release of radioactive materials from the nuclear plant during normal operations or as the result of accidents. The early development of nuclear reactors involved relatively small amounts of fuel and, consequently, small inventories of radioactive materials. There was a great deal of uncertainty about the safe performance of the early developmental reactors. A safety strategy pursued during those pioneering development activities was to locate the reactors on large government-owned reservations well isolated from the public. In the case of accidental release of radioactivity, the radioactive material would be so diluted by the time it reached the site boundary that it would pose no significant threat to the public.

The formulae used for the calculation of the dilution and deposition of radioactive materials release from a reactor included a term that described the magnitude and the duration of radioactive material release from the reactor. This term, usually designated by the symbol S or $\dot{S}$ in the equations, became known as the "source term." It has come to include a description of the physical and chemical forms of the released materials as well as the magnitude and duration of the release. A document produced in the early 1960s, Calculation of Distance Factors for Power and Test Reactors[1], provided an example source term that could be used in deterministic calculations to demonstrate that a reactor was sufficiently isolated from the public. This example source term has achieved greater significance as it has been adopted and adapted for the regulation of commercial power reactors in the USA [2,3]. The source term focuses on the radioactive noble gases, typically xenon and krypton, and radioactive iodine. One hundred percent of the noble gases are assumed to be released. Only 50% of the iodine is taken to be released from reactor fuel. Of this, only half is taken to be available for release from the plant. The released radioactive iodine is 91% gaseous I_2, 5% iodine-bearing particulate, and 4% a gaseous organic iodine compound.

Improvements in nuclear technology and the economies of scale led to the development of large nuclear power plants with large inventories of radionuclides. No sites in the USA could satisfy the isolation requirements for public safety based on distance factor formulae developed for the early research reactors. Additional safety measures were imposed. Among these measures was a requirement that nuclear power reactors be enclosed in stout containments, that would act as barriers to the release of radioactive materials into the environment where they would pose threats to the public. Deterministic analyses of radionuclide retention within containments also involved formulae with terms describing the magnitude and duration of radionuclide releases from the reactor and fuel into the containment. These terms were also called "source terms." Unlike the original source terms, these source terms refer only to the releases of radioactivity into the containment.

When very simplified source terms are used, such as those in references 1-3, there is not much confusion associated with source terms to the containment and source terms to the environment. The technical understanding of radionuclide release and behavior has advanced greatly and the source terms are now much more complicated. A persistent confusion exists concerning "source terms to the containment" and "source terms to the environment." This confusion has been magnified as interests have developed in evaluating public consequences of severe or beyond-design-basis reactor accidents. The Reactor Safety Study[4] demonstrated that public risks associated with the use of commercial nuclear power were due predominantly to these beyond-design-basis accidents. First attempts were made in the Reactor Safety Study to mechanistically calculate the release of radioactive materials from reactor fuel and the subsequent behaviors of these materials. These calculations demonstrated that natural and engineered processes could substantially attenuate the magnitudes of radionuclide releases to the environment even if containments were, eventually, ruptured in a reactor accident.

The technology first articulated in the Reactor Safety Study has been developed further since 1975--spurred, perhaps, by reactor accidents at Three Mile Island and Chernobyl. For representative accidents, it is now possible to make quite detailed, mechanistic calculations of both the source term to the containment and the source term to the environment[5]. Results of these representative calculations can be grouped and correlated for more routine, generic uses. The substantial body of technical knowledge has been assembled and examined to formulate an alternative to the source term to the containment described in reference 1. This alternative [6] describes more elements than does the older source term, as is shown by the comparison in Table 1. Different source terms are described for boiling water reactors and for pressurized water reactors. Because natural and engineered processes take time to attenuate releases to the containment, timing of the releases is a critical feature of the alternative source term. Beyond-design-basis accidents are divided into four phases:

- gap release phase,
- in-vessel release phase,
- ex-vessel release phase, and
- late in-vessel release phase.

Releases of radioactive materials are specified for each of these accident phases. Except for iodine and the noble gases, the radioactive materials released to the containment are taken to be aerosol particles. Iodine entering the containment is taken to be 95% particulate and 5% gaseous I or HI.

The alternative source terms to the containment described in reference 6 were chosen to somewhat conservatively bound source terms calculated for severe reactor accidents. As such, they represent one assessment of a conservative source term to use for regulatory purposes. It is of interest then to compare this source term to source terms used for regulation in other countries.

There has been active development of severe accident analyses in countries outside the USA. Attentions can be drawn to Phase B of the German Risk Study[7], the Public Inquiry for the Sizewell B plant in the United Kingdom[8], the RAMA Study in Sweden [9], development of the Thales computer codes in Japan[10], and the experimental studies and code development work in France[11]. In a qualitative sense, these various analyses of severe accident source terms to the containment and to the environment employ methods similar to those used in the USA. Of interest are quantitative differences.

In the subsections below, source terms being used in various countries are compared. In Section II source terms to the containment are discussed. In Section III source terms to the environment are described.

Table 1. Source Terms to the Containment

Release	Req. Guide*,** 1.3, 1.4 (1,2,3)	NUREG-1465* Boiling Water Reactors (6) gap	in-vessel	ex-vessel	late in-vessel	NUREG-1465* Pressurized Water Reactors (6) gap	in-vessel	ex-vessel	late in-vessel
Duration(s)	0	3600	5400	10800	36,000	1800	4680	7200	36,000
Radionuclide									
Xe, Kr	100	5	95	0	0	5	95	0	0
Iodine									
-gas	23.75	0.25	1.1	1.8	0.4	0.2	1.75	1.4	0.4
-particle	1.25	4.75	20.9	35.2	6.6	4.8	33.25	27.6	6.6
-total	25	5	22	37	7	5	35	29	7
Cesium	0	5	15	45	3	5	25	39	6
Tellurium	0	0	11	38	1	0	15	29	2.5
Strontium	0	0	3	24	0	0	3	12	0
Barium	0	0	3	21	0	0	4	10	0
Ruthenium	0	0	0.7	0.4	0	0	0.8	0.4	0
Cerium	0	0	0.9	1.0	0	0	1.0	2.0	0
Lanthanum	0	0	0.2	1.0	0	0	0.2	1.5	0

*Releases are given as percent of core inventory.
**Reference 1 calls for release of 1 percent of other radionuclides in particulate form.

II. Source Terms to the Containment

Information that has been assembled on the regulatory source terms to the containment used in various countries are summarily described in the subsections below:

A. France

The source term to the containment is not as much a focus of regulatory attention as source terms to the environment (see discussion, below). The current source term to the containment used for regulatory evaluations is:

Radionuclide Group	Release (% of Core Inventory)
Kr, Xe	100
I, Br, Cs, Rb	100
Te, Sb, Ag, Sn	100
Sr, Ba, Mo, Tc	10
Ru, Rh, As, In, Cd, Pd	10
Y, La, Ce, Pr, Nd, Pm, Sm, Eu, Gd	0.1
Np, Pu, Am, Cm	0.1

With the exception of the Te, Sb, Ag, Sn group release, this source term is quite comparable to that specified in NUREG-1465[6]. The release of the Te, Sb, Ag, Sn group is somewhat higher than what is specified in NUREG-1465.

B. Germany

Releases to the containment for the dominant accident sequence (total loss of feedwater) with subsequent opening of the pressurizer valves (primary bleed) and total failure of all active injection systems are:

Radionuclide	In-Vessel Phase (% of core inventory)	Ex-vessel Phase (% of core inventory)
Xe, Kr	100	-
I, Cs	85	-
Te	22	50
Sr	0.044	-
Ba	1.0	-
others	<0.001	-

C. Japan

Regulatory approaches to the source term to the containment are based on the so-called TID-14844 source term described in references 1, 2, and 3. There are plans to re-examine this approach in light of technical developments over the past several years.

D. Sweden

Sweden's regulatory authorities do not prescribe a radionuclide source term to the containment. The accident scenario chosen as a design basis for the 9 boiling water reactors and 3 pressurized water reactors is a total loss of power for 24 hours. Active accident management is taken to be possible 8 hours after accident initiation. In addition, boiling water reactors have a design basis accident involving a pipe break loss of coolant combined with failure of pressure suppression. Radionuclide source terms to the containment are calculated with the MAAP code. The MAAP code was validated for these purposes in the RAMA project [9].

E. United Kingdom

The United Kingdom is in the process of licensing a single pressurized water reactor. It is feasible, then, to apply mechanistic models to the prediction of source terms to the containment. The basic code being used for these analyses is MAAP. The analyses with MAAP are being supported by modified versions of VICTORIA, for in-vessel release phases, and CORCON, for ex-vessel release phases. The approach toward source terms is rather similar to that used in the NUREG-1150 study of five representative U.S. nuclear power plants[5].

F. United States

As of now, the source term to the containment for regulatory use is that specified in TID-14844 and modified as described in references 2 and 3. There is a proposal [6] of an alternative source term to be used for safety analyses of advanced reactors. This alternative source term may be adopted by operators of existing nuclear power plants.

III. Source Terms to the Environment

Source terms to the environment are, of course, critical inputs to the analyses of accident consequences. Typically, these source terms are cast in probabilistic risk analysis formulations so there is no single bounding source term. Rather, there are source term categories. The source term categories defined in the Reactor Safety Study[4] are shown in Table 2. The analyses that yielded these source term categories have been updated by the NUREG-1150 study[5]. This study defined quite a few more categories. For comparison purposes only, a risk dominant (individual risk at 1 mile from the plant) source term for the pressurized water reactor Surry (NUREG-1150, SUR-10-2) is shown in Table 2.

Source terms to the environment considered in other countries are described below:

A. **France**

France employs three bounding source terms to the environment, S1, S2, and S3. These source terms to the environment are shown in Table 3. The source term S1 involves the performance of no engineered safety features and is probably comparable to the PWR2 source term from the Reactor Safety Study or the risk dominant source term for Surry shown in Table 2. The S3 source term corresponds to release through a filtered venting system. The filtration reduces the magnitude of radionuclide release to the environment substantially.

B. **Germany**

Within the context of the German Risk Study[7], five source terms for various accident sequences are defined. These accident source terms to the environment are shown in Table 4. The source term for early containment failure is comparable to the more severe source terms considered for U. S. commercial nuclear power plants such as the PWR2 source term. Very much tighter restrictions on source terms to the environment are being imposed on future reactors.

C. **Japan**

Publicly available information on severe accident source terms to the environment calculated for Japanese reactors is scarce. Calculations are being done with the MAAP and MELCOR codes.

D. **Sweden**

A decree by the government of Sweden concerning accidental releases of radionuclides states:

- land contamination, which impedes the use of large areas for a long period, shall be prevented,
- acute radiation fatalities shall not occur,
- the specified maximum release of radioactive substances shall apply to all reactors irrespective of site or power, and
- extremely improbable events and scenarios need not be considered for meeting these requirements.

To comply with this decree, it is required that radionuclide releases must be limited to noble gases and at most 0.1% of the inventories of ^{134}Cs and ^{137}Cs in a reactor core of 1800 MW thermal power. It is assumed that other radionuclides of significance with regard to land contamination are released to a lesser, or at most equal, extent.

Table 2. **Severe Accident Source Terms to the Environment**

Release Category	Time(s)	Xe, Kr	Organic I	Inorganic I	Cs	Te	Ba, Sr	Ru	La
		Release*							
(Reference 4)									
PWR2	9000	90	0.7	70	50	30	6	2	0.3
PWR3	18000	80	0.6	20	20	30	2	3	0.4
PWR4	7200	60	0.2	9	4	3	0.5	0.3	0.3
PWR5	7200	30	0.2	3	0.9	0.5	0.1	0.06	0.04
PWR6	43200	30	0.2	0.08	0.08	0.1	9×10^{-3}	7×10^{-3}	7×10^{-3}
PWR7	3600	0.6	2×10^{-3}	2×10^{-3}	1×10^{-3}	2×10^{-3}	1×10^{-4}	1×10^{-4}	2×10^{-5}
PWR8	1800	0.2	5×10^{-4}	0.01	0.05	1×10^{-4}	1×10^{-6}	0	0
PWR9	1800	3×10^{-4}	7×10^{-7}	1×10^{-5}	6×10^{-5}	1×10^{-7}	1×10^{-9}	0	0
BWR1	1800	100	0.7	40	40	70	5	50	0.5
BWR2	10800	100	0.7	90	50	30	10	3	0.4
BWR3	10800	100	0.7	10	10	30	1	2	0.4
BWR4	7200	60	0.07	0.08	0.5	0.4	0.06	0.06	0.01
BWR5	18000	0.05	2×10^{-7}	6×10^{-9}	4×10^{-7}	8×10^{-10}	8×10^{-12}	0	0
NUREG-1150 SUR-10-2		76	0.8	15.2	16	31	20	5.2	2.2

*Percent of initial core inventory

Table 3. French Source Terms to the Environment

Radionuclide	Source Term* S1	S2	S3
Noble Gases	80	75	75
Iodine			
Organic	0.7	0.55	0.55
Inorganic	60	2.7	0.3
Cesium	40	5.5	0.35
Tellurium	8	5	0.4
Strontium	5	0.6	0.04
Ruthenium	2	0.5	0.03
Lanthanum	0.3	0.08	0.005
Cerium	0.3	0.08	0.005

*Percent of core inventory

Table 4. Source Terms to the Environment for Various Accidents in German Pressurized Water Reactors

	Source Term*		
Radionuclide	Early Containment Failure	Small Leak in Containment	Filtered Venting From Containment
Xe, Kr	100	100	90
Iodine	>50	0.8	0.2
Cesium	>50	0.04	3×10^{-5}
Tellruium	>50	0.2	4×10^{-4}
Strontium	40	0.02	2×10^{-5}
Start of Release(s)	>7200	21600	$>3.46 \times 10^{5}$

*Percent of core inventory.

E. **United Kingdom**

A full scope probabilistic risk assessment of the Sizewell B pressurized water reactor has been completed[12, 13, 14]. Results of the sequence analyses are collected together to define a variety of source term categories. These source term categories are defined based on the characteristics of radioactive material released from the containment such as the release duration and timing as well as the amount of radioactive material released. These source term categories are then grouped into a set of 22 release categories based on the effective dose at 80 meters from the plant (4 release categories) or the effective dose at 3 kilometers from the plant (18 release categories). The release categories involve doses of up to 1000 Sv at 3 km. Again, these release categories include more information than just the radionuclide makeup of the material released to the environment. Radionuclide compositions of the releases have not been published.

IV. Comparisons Among Source Terms

There is a broad comparability among the source terms being used in France, Germany, Japan, Sweden, the United Kingdom, and the USA. The technical bases for estimating the releases of radioactive materials to the reactor containment and from the nuclear plant into the environment are quite similar. It appears likely that for comparable accident scenarios, the predicted source terms would be rather similar. Differences among the estimated releases of radionuclides to the reactor containment are probably not as significant as are the differences between the TID-14844[1] source term which emphasized gaseous iodine and more modern estimates such as those in NUREG-1465[2] which emphasize particulate material. Comparison of predicted releases of radionuclides to the environment are more difficult to make because of differences in plant designs and the elaborate probabilistic framework surrounding the estimates. It is likely that predicted releases to the environment would be quite comparable for comparable accident scenarios at comparable plants.

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