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NRC Source Term Research
Outstanding Issues and Future Directions

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Regulatory Role of the Reactor Accident Source Term

The reactor accident source term arises in two distinct ways in the US regulatory process. The first is the release of radioactive material to the environment during a hypothetical reactor accident. This source term is an input to models of radionuclide dispersal and accident consequences. It drives measures taken for emergency preparedness and accident response. It is a crucial element of Level III probabilistic risk assessments and also arises in the cost-benefit analyses of safety improvements that go beyond regulatory requirements to provide adequate protection of public health and safety.

The second source term used in the regulatory process is the release of radioactive material to the reactor containment. This source term is used in the analysis of plant sites. It is a defense in depth measure to assess the adequacy of reactor containments and engineered safety systems. This source term also figures in the environmental qualification of equipment within the containment that must function following a design-basis accident.

Most of the currently operating power reactors in the USA were designed and licensed based on the so-called “TID-14844 source term”[1]. This source term was based on results of experiments involving the heatup of irradiated fuel fragments in a furnace. Releases to the containment prescribed by the TID-14844 source term are:

Radioactive Element	Percent of initial core inventory released to the containment	Physical form of the released material
Noble gases (Xe, Kr)	100 %	gas
Iodine	50 %	gas
All others	1 %	aerosol particles

The source term was assumed to be instantly available in the containment. Half the iodine was assumed to deposit in route to the containment. The source to the environment was found assuming the design basis leakage rate for the containment and attenuation of the radioactive material available for release by engineered safety features (sprays, suppression pools, ice beds, etc.) of the plant.

Following the accident at Three Mile Island, it was evident that radionuclide release did not closely follow the pattern that might be expected based on the TID-14844 source term. Pressure arose from the nuclear industry for a more realistic source term. The Nuclear Regulatory Commission asked the Office of Regulatory Research if it could define a more realistic source term and if that source term would be smaller than that used for reactor licensing. The Office of Regulatory Research reply [2] was that insufficient data were available for defining a more realistic source term, but that it was possible to obtain the needed data and provide such a definition. The Office was directed by the Commission to undertake the required research.

Mechanistic Reactor Accident Source Terms

The route to a more realistic accident source term defined by the Office of Nuclear Regulatory Research was to develop a mechanistic linkage of radionuclide behavior including release from fuel and transport to the containment to reactor accident phenomena. Earlier work done as part of the Reactor Safety Study [3] to develop mechanistic accident source terms had been hampered by insufficient understanding of accident phenomena. Consequently, the research effort undertaken was very broad in scope. It involved the experimental investigation of core degradation, steam explosions, hydrogen combustion, fission product transport, core debris interactions with concrete and even the structural response of reactor containments. Major developments in the science of aerosol transport were necessary. Eventually, more than half a billion dollars were spent on the effort.

The research on the reactor accident source term led to the development of the Source Term Code Package. This was a suite of “stand-alone” computer codes linked together to mechanistically predict for a variety of accidents the source term to the reactor containment and the attenuation of the inventory of radionuclides in the containment as a result of natural and engineered processes. This first phase of the NRC’s study of mechanistic reactor accident source terms culminated in the publication of improved source terms for use in regulatory processes [4] and publication of level III analysis of accident risks at representative US nuclear power plants [5]. Source terms for use in the regulatory process were developed for generic pressurized water reactors and boiling water reactors. In both, it is recognized that the release of radioactivity progressed in time. Accidents are divided into four phases: gap release, in-vessel release, ex-vessel release, and late in-vessel release. The fourth of these phases accounts for the revaporization of radionuclides deposited within the reactor during early phases of an accident. Release fractions of eight radionuclide groups are prescribed for each of these accident phases. With the exception of noble gases and iodine, all releases are presumed to be in the form of aerosol particles. Most of the iodine is presumed to be released to the containment as particulate, but 5% is taken to be gaseous and a fraction of this gaseous iodine is taken to be a volatile organic iodide.

The revised regulatory source terms have proven to be quite popular with licensees even though they do not greatly alter the amount of radioactivity that must be assumed to be released to the containment. They do change the timing of the release to the containment and this has allowed licensees seek relief from regulatory restrictions associated with the timing. Changes made in such areas as diesel generator startup times and main steam isolation valve closure times improve the reliabilities of these systems and consequently improve plant safety.

The level III risk analysis of representative plants was a monumental repetition of the Reactor Safety Study with better computational methods and additional plants. Analyses were done for three pressurized water reactors (ice condenser, sub-atmospheric and large dry containments) and two boiling water reactors (Mark I and Mark III containments). A study of a Mark II containment boiling water reactor was done in parallel. A most important aspect of the study was the comprehensive examination of uncertainties in the modeling of accident progression and radionuclide behavior. Convolution and propagation of parametric uncertainties through mechanistic models allowed uncertainty ranges for radionuclide releases to be defined and identified critical areas of remaining uncertainty concerning accident source terms.

Ongoing Source Term Research

The first phase of NRC's investigation of reactor accident source terms met the immediate regulatory needs. It was, however, well recognized that the understanding that had been developed through research was hardly complete. As nuclear power plants evolved and additional use was made of quantitative risk assessment in the regulatory process, better understanding of reactor accident source terms would be needed. The strategy for continued research involved two main thrusts:

- Development of an integrated model of severe accident progression to preserve and further develop the knowledge and understanding of severe reactor accidents gained from research.
- Collaboration internationally on continued experimental investigation of severe reactor accident and source term phenomena.

The Source Term Code Package code suite was replaced by the integrated, systems level accident analysis computer code MELCOR [6]. NRC is gratified that some many other institutions have taken an interest in using and further developing the MELCOR computer code.

Several international collaborative research activities have been undertaken, including:

- PHEBUS-FP
- ARTIST
- RASPLAV and MASCA
- MACE
- Lower Head Failure Tests

The integrated fission product behavior tests in the PHEBUS-FP program were viewed as particularly crucial. Research had established that the chemical forms adopted by fission products during an accident had an important bearing on the behaviors of these fission products. Assumptions concerning assumed forms of these fission products were regularly refuted by experimental studies of various types. Prediction of chemical forms was made difficult by the diversity of possibilities in so complicated an environment as a reactor accident. Better guidance based on prototypical combinations of materials in realistic environments was needed to improve modeling capabilities. The investment in the PHEBUS-FP tests has been beneficial and the US is now participating in follow-on studies to understand better the complicated chemistries of iodine and cesium under reactor accident conditions.

Risk analyses have shown that reactor accidents involving radionuclide release paths that bypass reactor containments pose high levels of risk. Accidents initiated by steam generator tube ruptures in pressurized water reactors are particularly important examples. Uncertainty analyses of such accidents have shown that source term mitigation by structures and the like on the secondary sides of steam generators was poorly understood. The ARTIST tests have provided prototypic experimental data that will allow this mitigation to be better modeled in accident analysis computer codes.

Results of the other international collaborative research activities are also having important impacts on computer modeling of severe reactor accidents and the regulatory process. For example, the RASPLAV and MASCA experimental programs have provided data important for regulatory review of in-vessel retention of reactor core debris such as in the advanced light water reactor AP1000. The MACE tests have provided important information on cooling and source term attenuation by water overlying core debris interacting with structural concrete.

NRC is now going beyond just the source term to the environment and is examining realistic predictions of accident consequences. The State-of-the-Art Consequence Analysis (SOARCA) project will examine potential accident consequences at the Peach Bottom boiling water reactor and the Surrey pressurized water reactor.

Future Directions of Source Term Research

Many light water reactor source term issues of interest to the regulatory process remain to be researched. Interest continues in:

- Understanding the formation of gaseous iodine in reactor containments and the need for buffers in sump waters.
- Effects of high burnup (> 60 GWd/t) on fission product release from conventional low-enrichment uranium dioxide fuels.
- Fission product release from mixed oxide fuels (MOX).
- The effect of air on fission product release and behavior both in the late stages of reactor accidents and in accidents involving spent fuel storage pools.

In the somewhat longer term, source term research for advanced reactor fuels will need to be considered. NRC has recently completed an exercise to identify and rank phenomena that will affect fission product release from high temperature gas reactor fuel [7]. A similar phenomena identification and ranking activity is now underway for fission product transport and accident progression. Early steps are being taken to identify experimental studies that will be needed to support modeling of fission product behavior in accidents at gas-cooled reactors. It is anticipated that there will be international interest in such experimental studies.

On the horizon is the US Department of Energy's Global Nuclear Energy Partnership program that is investigating the feasibility of developing a liquid metal cooled actinide burner reactor as part of a strategy to close the nuclear fuel cycle. As this project engages the regulatory process, there will be needs to understand source issues both for the sodium-cooled fast reactor and the associated fuel fabrication and reprocessing facilities. Additional analytic and experimental investigations will, no doubt, be needed.

References:

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