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Use of PHEBUS-FP Results in the NRC R&D Programme on Severe Accidents

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INTRODUCTION

Following the accident at Three Mile Island, the U.S. Nuclear Regulatory Commission (NRC) undertook a significant research effort to better understand reactor accidents that go beyond the design bases of U.S. nuclear power plants [1]. This effort was directed initially at obtaining a more realistic source term of radionuclides to be used in safety analyses of power plants. At the time, the so-called "TID-14844 source term" [2] was used for these safety analyses. This source term, which was devised in the 1960s, hypothesized that "severe" accidents would produce a source term of radionulcides to the containment of reactor composed primarily of noble gases and iodine in gaseous form. Events during the accident at Three Mile Island suggested that this prescription for radionulcide release to the containment might be overly conservative. Iodine released to the containment might not be entirely in gaseous form and assuredly the complete release of radioactive material to the containment was not instantaneous as was hypothesized in the safety analyses. The outcome of this aspect of the NRC research program has been a revised source term for use in reactor safety analyses [3]. Confirmation of the adequacy of this revised source term is expected to come, at least in part, from results of the PHEBUS-FP tests. Details on the NRC plans in this regard are discussed in the second section of this paper.

The effort to understand severe accident phenomena evolved with time to provide general technical support for the development of a technical understanding of severe accidents for probabilistic risk assessments. In this evolution, the undertaking built upon the mechanistic modeling of accident phenomena, loads on reactor containments and radionuclide behavior developed for the WASH 1400 study [4] of residual risks posed by the use of commercial power reactors. Support for the analysis of accident progression and fission product release has become especially important as NRC modifies it reactor regulations to become more risk informed.

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DISCLAIMER

The objectives of the research by NRC are to develop computer models of accident processes and fission product release that could be used to make predictions for the wide range of accident conditions considered in risk assessments. In the course of the work, it became apparent that substantially more detailed and sophisticated models would be needed to gain an understanding of the sensitivity of important physical and chemical processes. Such detailed models were needed to interpret properly many integral and separate effects test being conducted throughout the world.

Consequently, the work being undertaken by the NRC was organized into what became known as the "two-tier code strategy". This strategy involved the parallel development of detailed, mechanistic models of individual severe accident processes along with development of a systems-level model, MELCOR, that addressed all important phenomena in an integrated, but less detailed, manner. Modeling detail in the systems-level code is determined to a significant extent by findings from the models of individual phenomena and, especially, from the comparison of model predictions to results of experiments.

Detailed phenomenological models that have been used to assist the development of NRC's system-level model, MELCOR, include:

- SCDAP: a model of core degradation under severe accident conditions
- CONTAIN: a model of containment response to severe accident phenomena
- HECTR: a model of hydrogen combustion
- MAEROS: a model of aerosol agglomeration and transport
- CORCON: a model of core debris interactions with concrete
- VANESA: a model of radionuclide release during core debris interactions with concrete
- CORSOR: a model of radionuclide release from degrading reactor fuel
- IFCI: a model of molten fuel interactions with water
- INSPECT and LIRIC: mechanistic models of aqueous iodine chemistry

The incorporation of these models into MELCOR has followed three possible paths. In some cases, the phenomenological models were incorporated directly into MELCOR. This was done for example with the models HECTR, CORCON, CORSOR, and VANESA. In other cases, models were derived for MELCOR and adjusted to produce predictions approximately equivalent to those produced by the phenomenological codes. This pathway was followed for the modeling of core degradation as done by the SCDAP code and containment response as done by the CONTAIN code.

The third pathway for introducing phenomenology into the systems-level code has been to develop for the systems-level code a deliberately simplified model that includes only the most important features identified from the detailed phenomenological models. This is the pathway that is being pursued for the prediction of fission product transport and deposition in the reactor coolant system. These transport and deposition processes are modeled in detail in the VICTORIA code.

Satisfactory comparison of model predictions to the results of realistic experiments is, of course, the crucial test of technical adequacy. Comparison of model predictions with results of separate effects tests are often necessary for the development and evaluation of phenomenological models of individual processes. Integral experiments at substantial scales are especially useful for validation of the systems-level modeling. Such tests provide information on the individual processes and also information on the modeling interfaces among individual phenomena. These interfaces are especially important since they constitute models themselves that otherwise are very difficult to test. It is for this reason that the NRC is so interested in using the results of the PHEBUS-FP integral tests. These tests integrate core degradation, fission product release, fission product transport in a model of a reactor coolant system and fission product behavior in a model of the reactor containment. NRC views the PHEBUS-FP as an important part of its strategy to validate its systems-level model MELCOR. Additional details on the NRC's plans to use the results of the PHEBUS-FP tests in this way are provided in the third section of this paper.

THE REVISED ACCIDENT SOURCE TERM

Based on phenomenological and analytic severe accident research, the NRC has formulated a revised accident source term for use in reactor regulatory analyses. This revised source term, often called the NUREG-1465 source term, provides a more realistic description of radionuclide releases to the containment in a severe reactor accident. Distinct source terms are specified for PWRs and BWRs as shown in Table 1. There are releases to the containment of fission products in 8 element categories that occur during four phases of an accident - fuel cladding rupture, fuel degradation, core debris/concrete interactions and late phase revaporization processes. Some important features of the source term are:

- releases to the containment are time dependent
- all radiologically important elements are considered
- iodine is specified to be released predominantly as metal iodide particles, but a fraction (5%) is also specified to be gaseous (HI, I_2, CH_3I, etc.)
- both radionuclide deposition in the reactor coolant system and revaporization of the deposited materials have been considered in developing the description of release to the containment
- rather small fractional releases of the refractory metal fission products (Ru, Mo, etc.) and the refractory oxide fission products (CeO_2, La_2O_3, etc.) are prescribed.

Many of these important features of the revised accident source term are subject to verification by results of the PHEBUS-FP test. It has already been learned from the preliminary results of the FPT0 and FPT1 tests that it was prudent to include in the iodine source term some allowance for a fraction of the iodine entering the containment in a gaseous form. Whether this allowance for 5% gaseous iodine is overly generous is now to be evaluated by examination of the finalized results of the PHEBUS tests. The forthcoming FPT2 test will provide data to show if boric acid

Table 1. Revised accident source terms for BWRs and PWRs.

BWR	Gap Release	Early In-vessel Release	Ex-vessel Release	Late In-vessel Release
Duration (Hours)	0.5 hours	1.5 hours	3.0 hours	10 hours
Noble gases	5%	95%	0	0
Halogens	5%	25%	30%	1%
Alkali Metals	5%	20%	35%	1%
Chalcogens	0	5%	25%	0.5%
Barium & Strontium	0	2%	10%	0
Refractory Metals	0	0.25%	0.25%	0
Cerium Group	0	0.05%	0.5%	0
Lanthanum Group	0	0.02%	0.5%	0

PWR	Gap Release	Early In-vessel Release	Ex-vessel Release	Late In-vessel Release
Duration (Hours)	0.5 hours	1.3 hours	2.0 hours	10 hours
Noble gases	5%	95%	0	0
Halogens	5%	35%	25%	10%
Alkali Metals	5%	25%	35%	10%
Chalcogens	0	5%	25%	0.5%
Barium & Strontium	0	2%	10%	0
Refractory Metals	0	0.25%	0.25%	0
Cerium Group	0	0.05%	0.5%	0
Lanthanum Group	0	0.02%	0.5%	0

in the reactor coolant system affects the fraction of iodine in the gaseous state either during initial release or during the subsequent revaporization as a result of reactions such as:

$$HBO_2 + CsI \rightleftarrows CsBO_2 + HI(g)$$

$$2CsI + n\,B_2O_3 + H_2O \rightleftarrows Cs_2B_{2n}O_{3n+1} + 2\,HI(g)$$

$$2HI(g) \rightleftarrows H_2 + 2I(g)$$

Release of boron oxides to the reactor coolant system from the degradation of boron carbide control materials planned for the FPT-3 test will provide data on the effects of boron on iodine chemistry in the context of accidents at boiling water reactors.

The recently completed test of release from debris beds of fuel (the FPT-4 test) much like those observed to develop during the accident at Three Mile Island should provide data on the need for possible improvements in the revised accident source term. Some have suggested that at the high temperatures reached in such debris beds, larger releases of refractory fission products may occur.

The planned FPT-5 test of the effects of air intrusion into the reactor coolant system is expected to indicate if there are needs to account in the revised source term for larger releases of refractory metal fission products such as ruthenium and molybdenum. Earlier tests in the PHEBUS-FP project have suggested a higher mobility of ruthenium, especially, than had been anticipated.

VALIDATION OF MELCOR MODELING

The validation of the revised accident source term that will come from the PHEBUS-FP experimental results is primarily qualitative. Results of the experimental program are expected to have both qualitative and quantitative effects on the NRC's systems-level accident analysis code, MELCOR. The quantitative effects will be on important models already in the code. From the information obtained in the first two tests (FPT0 and FPT1), it has been found that accurate modeling of the phase relations in the Zr-U-O system is needed to predict well the relocation of fuel from the core region as degradation of the core progresses. Similarly, it has been learned that in accidents involving silver-indium-cadmium control blades, reaction of CsI to form water-insoluble AgI must be modeled to accurately predict the behavior of iodine in reactor containments.

It is expected that the results of the first two tests will provide additional data for selection of parameters in the modeling of fission product releases from the fuel. It also appears that there may be data from the tests that are sufficient to resolve the question of whether aerosol nucleation needs to be explicitly modeled in a systems-level accident analysis code. It is hoped that the first two tests as well as the remaining tests will indicate if the limited fission product speciation adopted in the MELCOR code is adequate.

Most of the PHEBUS -FP tests (the exception being the FPT4 test) will yield data on the partitioning of iodine from water in the containment sump into the containment atmosphere. Whereas a fairly detailed understanding is now available on the chemistry of iodine that leads to this partitioning in chemically simple systems, there is not a rich data base on the chemical effects of the many other things that will be present in water and the atmosphere during actual reactor accidents. It is entirely possible that a much more complete modeling of aqueous chemistry might be needed to predict the fraction of iodine that partitions from water back into the containment atmosphere where it could be released into the environment. The PHEBUS-FP results on the partitioning of iodine from water into the atmosphere will reflect some of this more realistic chemistry since the mix of materials coming into sump waters along with iodine is quite prototypic in most respects. It is anticipated, then, that the results of the PHEBUS test will provide a good indication of whether the existing iodine chemistry model in MELCOR, which has been tested against the simpler RTF tests done in Canada, is adequate for predictions of iodine chemistry under reactor accident conditions.

Important products of the first two tests in the PHEBUS-FP program have been fine data sets on the deposition of aerosols in the reactor circuit especially in the region of the steam generator tube between points C and G. It is thought that these data sets as well as those to be obtained from future tests will be useful in the validation of the aerosol deposition models in MELCOR. The data ought to be of use in validating the thermophoretic deposition model. They may be of use in validating the procedure used in MELCOR to sum the effects of gravitation, thermophoresis and turbulence on aerosol deposition. Use of the data in this way will require that there are also good data sets on the gas phase concentrations of aerosol particles and particle sizes.

It is anticipated that subsequent tests in the PHEBUS-FP program will qualitatively affect the modeling in MELCOR. It is anticipated that results of the FPT-4 test will indicate if modeling of fission product release from debris beds must be included in the code. Results of the test FPT-5 will indicate if the code must make allowances for the possibility of air intrusion into the reactor coolant system following vessel penetration by core debris to predict adequately the severe accident source term and especially the releases of refractory metal fission products such as ruthenium. Tests FPT-2 and FPT-3 should provide an indication of whether it is necessary to include in the MELCOR modeling of core degradation the phenomenon of fuel swelling and foaming as a result of pressurization by fission gases.

THE VALIDATION PROCEDURE

To a very real extent, the NRC believes that it has developed a set of computational tools adequate to support its near term needs for the analysis of severe reactor accident and to support probabilistic risk assessments. Validation of its models by comparison with the results of the PHEBUS-FP tests is a most important step in the process of finalizing these tools for routine use. Because of the importance that will be attached to these comparisons, NRC has been reluctant to do comparisons on preliminary data coming from the PHEBUS-FP program. Instead, the NRC has been willing to wait until final data are available from each of the tests together with assessments of the uncertainties in the experimental results. NRC feels that the uncertainty analyses of the experimental data are essential to establishing criteria to assess the comparisons of code predictions to the experimental results. The PHEBUS tests are quite prototypic with respect to elemental compositions. It is, however, also important to understand the scaling of the thermohydraulic and mass transport characteristics of the tests relative to reactor accidents. NRC feels, then, that scaling analyses and out-of-pile tests planned by the project will contribute to the utility of the test results for validation of severe accident models.

REFERENCES

1. Office of Nuclear Regulatory Research, **Technical Bases for Estimating Fission Product Behavior During LWR Accidents**, NUREG-0772, U.S. Nuclear Regulatory Commission, Washington, D.C., 1981.

2. J.J. DiNunno et al., **Calculation of distance Factors for Power and Test Reactor Sites**, Technical Information Document, TID-14844, U.S. Atomic Energy Commission, Washington, D.C., 1962.

3. L. Soffer, S.B. Burson, C.M. Ferrell, R.Y. Lee, and J.N. Ridgely, **Accident Source Terms for Light-Water Nuclear Power Plants**, NUREG-1465, U.S. Nuclear Regulatory Commission, Washington, D.C., February, 1995.

4. U.S. Nuclear Regulatory Commission, **Reactor Safety Study: An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants**, WASH-1400, (NUREG-75/014), December 1975.