UNITED STATES
NUCLEAR REGULATORY COMMISSION
ADVISORY COMMITTEE ON REACTOR SAFEGUARDS
WASHINGTON, DC 20555 - 0001

November 21, 2013

Dr. Brian Sheron, Director
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

SUBJECT: ACRS ASSESSMENT OF THE QUALITY OF SELECTED NRC RESEARCH PROJECTS- FY 2013

Dear Dr. Sheron:

Enclosed is our report on the quality assessment of the following research projects:

- Application of Model Abstraction Techniques to Simulate Transport in Soils, NUREG/CR-7026
  - This project was found to be more than satisfactory, a professional work that satisfies research objectives.

- Fuel Fragmentation, Relocation, and Dispersal During the Loss-of-Coolant Accident, NUREG-2121
  - This project was found to be satisfactory. With some limitations, the results meet the research objectives. We encourage the author of this report to prepare a review paper for archival publication, after considering our review comments. .

These projects were selected from a list of candidate projects suggested by the Office of Nuclear Regulatory Research (RES).

We anticipate receiving a list of candidate projects for quality assessment in FY-2014 prior to our February 6-8, 2014 meeting.

Sincerely,

/RA/

J. Sam Armijo
Chairman

Enclosure: As stated

November 20, 2013

Dr. Brian Sheron, Director
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

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OFFICE	ACRS	SUNSI Review	ACRS	ACRS	ACRS
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DATE	11/20/13	11/20/13	11/20/13	11/20/13	11/20/13

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Assessment of the Quality of Selected NRC Research Projects by the Advisory Committee on Reactor Safeguards - FY 2013

November 2013

U.S. Nuclear Regulatory Commission
Advisory Committee on Reactor Safeguards
Washington, DC 20555-0001

ABOUT THE ACRS

The Advisory Committee on Reactor Safeguards (ACRS) was established as a statutory Committee of the Atomic Energy Commission (AEC) by a 1957 amendment to the *Atomic Energy Act* of 1954. The functions of the Committee are described in Sections 29 and 182b of the Act. The *Energy Reorganization Act* of 1974 transferred the AEC's licensing functions to the U.S. Nuclear Regulatory Commission (NRC), and the Committee has continued serving the same advisory role to the NRC.

The ACRS provides independent reviews of, and advice on, the safety of proposed or existing NRC-licensed reactor facilities and the adequacy of proposed safety standards. The ACRS reviews power reactor and fuel cycle facility license applications for which the NRC is responsible, as well as the safety-significant NRC regulations and guidance related to these facilities. The ACRS also provides advice on radiation protection, radioactive waste management and earth sciences in the agency's licensing reviews for fuel fabrication and enrichment facilities and waste disposal facilities. On its own initiative, the ACRS may review certain generic matters or safety-significant nuclear facility items. The Committee also advises the Commission on safety-significant policy issues, and performs other duties as the Commission may request. Upon request from the U.S. Department of Energy (DOE), the ACRS provides advice on U.S. Naval reactor designs and hazards associated with the DOE's nuclear activities and facilities. In addition, upon request, the ACRS provides technical advice to the Defense Nuclear Facilities Safety Board.

ACRS operations are governed by the *Federal Advisory Committee Act* (FACA), which is implemented through NRC regulations at Title 10, Part 7, of the *Code of Federal Regulations* (10 CFR Part 7). ACRS operational practices encourage the public, industry, State and local governments, and other stakeholders to express their views on regulatory matters.

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Mr. John W. Stetkar (Vice- Chairman), Principal, Stetkar & Associates, Lake Forest, California

ABSTRACT

In this report, the Advisory Committee on Reactor Safeguards (ACRS) presents the results of its assessment of the quality of selected research projects sponsored by the Office of Nuclear Regulatory Research (RES) of the NRC. An analytic/deliberative methodology was adopted by the Committee to guide its review of research projects. The methods of multi-attribute utility theory were utilized to structure the objectives of the review and develop numerical scales for rating the project with respect to each objective. The results of the evaluations of the quality of the two research projects are summarized as follows:

- Application of Model Abstraction Techniques to Simulate Transport in Soils, NUREG/CR-7026
    - This project was found to be more than satisfactory, a professional work that satisfies research objectives.
- Fuel Fragmentation, Relocation, and Dispersal During the Loss-of-Coolant Accident, NUREG-2121
    - This project was found to be satisfactory. With some limitations, the results meet the research objectives.

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ABBREVIATIONS

ACRS	Advisory Committee on Reactor Safeguards
AEC	Atomic Energy Commission
ANN	Artificial neural networks
ANS	American Nuclear Society
BWR	Boiling Water Reactor
BTC	Breakthrough curves
CFR	Code of Federal Regulation
CV	Coefficient of variation
DGPS	Differential Global Positioning System
EM	Electromagnetic Induction
ET	Evapotranspiration
FACA	Federal Advisory Committee Act
FAO	Food and Agriculture Organization of the United Nations
FEMWATER	Finite element model for groundwater
FY	Fiscal Year
GMS	Groundwater Modeling System
GPRA	Government Performance and Results Act
GWD	Groundwater depth
HPLC	High performance liquid chromatography
HYDRUS	Software package for simulating the movement of water, heat and multiple solutes in variably-saturated media
IC	Ion chromatography
IORV	Inadvertent Open Relief Valve
LOCA	Loss of Coolant Accident
LWR	Light Water Reactor
MA	Model Abstraction
MAUT	Multi-Attribute Utility Theory
MCP	Multi-sensor capacitance probes
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
PFBA	Perfluorobutyric acid
PTF	Pedotransfer function
PVC	Polyvinyl Chloride
PWR	Pressurized Water Reactor
RES	Office of Nuclear Regulatory Research
REV	Representative elementary volume
SCL	Sandy Clay Loam
SiltCL	Silt Clay Loam
SiltL	Silt Loam
SL	Sandy Loam
SOW	Statement of Work
U.S.	United States
TDR	Time Domain Reflectometry

ACKNOWLEDGMENT

The Committee would like to acknowledge the contribution of Dr. William Hinze, ACRS Consultant, in assessing the quality of the project, "Application of Model Abstraction Techniques to Simulate Transport in Soils," NUREG/CR-7026.

1 INTRODUCTION

The Nuclear Regulatory Commission (NRC) maintains a safety research program to ensure that the agency's regulations have sound technical bases. The research effort is needed to support regulatory activities and agency initiatives while maintaining an infrastructure of expertise, facilities, analytical tools, and data to support regulatory decisions.

The Office of Nuclear Regulatory Research (RES) is required to have an independent evaluation of the effectiveness (quality) and utility of its research programs. This evaluation is required by the NRC Strategic Plan that was developed as mandated by the Government Performance and Results Act (GPRA). Since fiscal year (FY) 2004, the Advisory Committee on Reactor Safeguards (ACRS) has been assisting RES by performing independent assessments of the quality of selected research projects [1-9]. The Committee established the following process for conducting the review of the quality of research projects:

- RES submits to the ACRS a list of candidate research projects for review because they have reached sufficient maturity that meaningful technical review can be conducted

- The ACRS selects a maximum of four projects for detailed review during the fiscal year.

- A panel of three to four ACRS members is established to assess the quality of each research project.

- The panel follows the guidance developed by the ACRS full Committee in conducting the technical review. This guidance is discussed further below.

- Each panel assesses the quality of the assigned research project and presents an oral and a written report to the ACRS full Committee for review. This review is to ensure uniformity in the evaluations by the various panels.

- The Committee submits an annual summary report to the RES Director.

Based on our later discussions with the RES, the ACRS made the following enhancements to its quality assessment process:

- After familiarizing itself with the research projects selected for quality assessment, each panel holds an informal meeting with the RES project manager and representatives of the User Office to obtain an overview of the project and the User Office's insights on the expectations for the project with regard to their needs.

- In addition, if needed, an additional informal meeting would be held with the project manager to obtain further clarification of information prior to completing the quality assessment.

The purposes of these enhancements were to ensure greater involvement of the RES project managers and their program office counterparts during the review process and to identify objectives, user office needs, and perspectives on the research projects.

An analytic/deliberative decisionmaking framework was adopted for evaluating the quality of NRC research projects. The definition of quality research adopted by the Committee includes two major characteristics:

- Results meet the objectives
- The results and methods are adequately documented

Within the first characteristic, the ACRS considered the following general attributes in evaluating the NRC research projects:

- Soundness of technical approach and results
  - Has execution of the work used available expertise in appropriate disciplines?

- Justification of major assumptions
  - Have assumptions key to the technical approach and the results been tested or otherwise justified?

- Treatment of uncertainties/sensitivities
  - Have significant uncertainties been characterized?
  - Have important sensitivities been identified?

Within the general category of documentation, the projects were evaluated in terms of the following measures:

- Clarity of presentation
- Identification of major assumptions

In this report, the ACRS presents the results of its assessment of the quality of the research projects associated with:

- Application of Model Abstraction Techniques to Simulate Transport in Soils

- Fuel Fragmentation, Relocation, and Dispersal during the Loss-of-Coolant Accident

These two projects were selected from a list of candidate projects suggested by RES.

The methodology for developing the quantitative metrics (numerical grades) for evaluating the quality of NRC research projects is presented in Section 2 of this report. The results of the assessment and ratings for the selected projects are discussed in Section 3.

2 METHODOLOGY FOR EVALUATING THE QUALITY OF RESEARCH PROJECTS

To guide its review of research projects, the ACRS has adopted an analytic/deliberative methodology [10-11]. The analytical part utilizes methods of multi-attribute utility theory (MAUT) [12-13] to structure the objectives of the review and develop numerical scales for rating the project with respect to each objective. The objectives were developed in a hierarchical manner (in the form of a “value tree”), and weights reflecting their relative importance were developed. The value tree and the relative weights developed by the full Committee are shown in Figure 1.

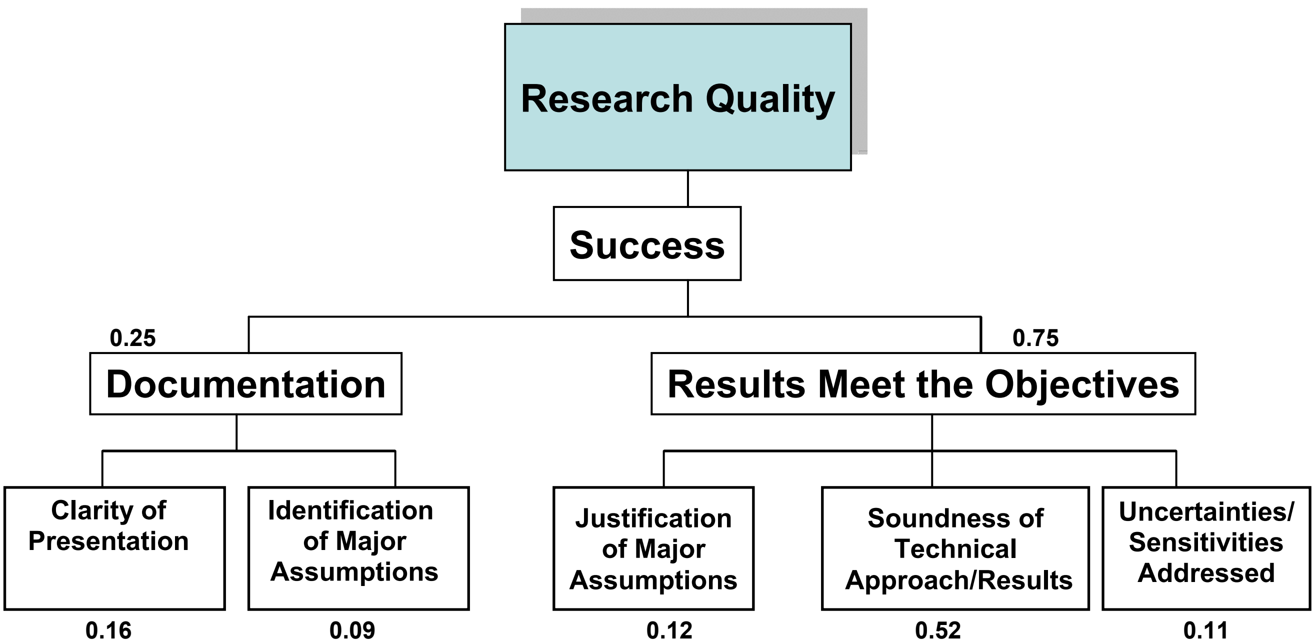

Figure 1 The value tree used for evaluating the quality of research projects

The quality of projects is evaluated in terms of the degree to which the results meet the objectives of the research and of the adequacy of the documentation of the research. It is the consensus of the ACRS that meeting the objectives of the research should have a weight of 0.75 in the overall evaluation of the research project. Adequacy of the documentation was assigned a weight of 0.25. Within these two broad categories, research projects were evaluated in terms of subsidiary “performance measures”:

- justification of major assumptions (weight: 0.12)
- soundness of the technical approach and reliability of results (weight: 0.52)
- treatment of uncertainties and characterization of sensitivities (weight: 0.11)

Documentation of the research was evaluated in terms of the following performance measures:

- clarity of presentation (weight: 0.16)
- identification of major assumptions (weight: 0.09)

To evaluate how well the research project performed with respect to each performance measure, constructed scales were developed as shown in Table 1. The starting point is a rating of 5, Satisfactory (professional work that satisfies the research objectives). Often in evaluations of this nature, a grade that is less than excellent is interpreted as pejorative. In this ACRS evaluation, a grade of 5 should be interpreted literally as satisfactory. Although innovation and excellent work are to be encouraged, the ACRS realizes that time and cost place constraints on innovation. Furthermore, research projects are constrained by the work scope that has been agreed upon. The score was, then, increased or decreased according to the attributes shown in the table. The overall score of the project was produced by multiplying each score by the corresponding weight of the performance measure and adding all the weighted scores.

As discussed in Section 1, a panel of three ACRS members was formed to review each selected research project. Each member of the review panel independently evaluated the project in terms of the performance measures shown in the value tree. The panel deliberated the assigned scores and developed a consensus score, which was not necessarily the arithmetic average of individual scores. The panel's consensus score was discussed by the full Committee and adjusted in response to ACRS members' comments. The final consensus scores were multiplied by the appropriate weights, the weighted scores of all the categories were summed, and an overall score for the project was produced. A set of comments justifying the ratings was also produced.

Table 1. Constructed Scales for the Performance Measures

SCORE	RANKING	INTERPRETATION
10	Outstanding	Creative and uniformly excellent
8	Excellent	Important elements of innovation or insight
5	Satisfactory	Professional work that satisfies research objectives
3	Marginal	Some deficiencies identified; marginally satisfies research objectives
0	Unacceptable	Results do not satisfy the objectives or are not reliable

3. RESULTS OF QUALITY ASSESSMENT

3.1 Application of Model Abstraction Techniques to Simulate Transport in Soils

The U.S. NRC review of performance assessments of nuclear facilities often involves assessing models for subsurface water flow and solute transport in the vicinity of a nuclear facility. These models seek to represent complex and highly transient subsurface systems. A representation of those complex systems in existing models ranges from very simple to extremely sophisticated formulations. Various methods to the selection or derivation of simple models for use along with more complex models have been utilized. One of the methods consists of systematic derivation of simpler models from the original complex model. This method has been termed "model abstraction" [14].

The NRC staff, in collaboration with the experts from the United States Department of Agriculture (USDA) Agricultural Research Service (ARS), Department of Environmental Hydrology & Microbiology of Ben-Gurion University of the Negev, and Department of Mechanical Engineering of Federal University of Rio de Janeiro has recently completed a study of the Application of Model Abstraction Techniques to Simulate Transport in Soils. This work was partially supported by an interagency agreement between the NRC and USDA Agricultural Research Service. The results of this effort are documented in NUREG/CR-7026, "Application of Model Abstraction Techniques to Simulate Transport in Soils" [14]. The scope of this quality review is limited to this report.

The objective of this project was to develop a test example of the application of model abstraction to solute transport in a field soil. The work was designed to be an intensive study that included a variety of advanced methods for characterizing, monitoring, and modeling flow and transport processes in a variably-saturated subsurface (or vadose) zone [14]. The project benefitted greatly from using the very well characterized USDA experimental field site near Beltsville, Maryland, where the subsurface hydrologic and solute transport processes have been studied for more than a decade before this particular study began [14].

<u>**General Observations**</u>

The movement of water in the vadose zone is a complex process involving numerous parameters that are likely to vary in time and space. These complications are primarily a result of the heterogeneity of the subsurface materials that can drastically affect the transport of water in its movement from the surface to the groundwater. The common assumption of 1-D, vertical movement from the surface to the groundwater is generally unwarranted because of the presence of variable hydrologic permeability within the vadose zone that causes lateral water infiltration. Accordingly, the nature of the transport process requires complex analytical models to investigate the movement of water and commonly involves a number of input parameters that are inadequately known. Unfortunately, these complex (base) models, which propagate uncertainty in the process and parameters, require significant resources. In addition these models are not sufficiently transparent and their use and results may not be readily interpretable and useful to the end user. As a result it is advantageous to abstract the modeling process using simplifying assumptions while maintaining the validity of the simulation. The objective of this project was to illustrate the use of model abstraction techniques to a shallow groundwater situation involving a variably-saturated vadose zone and show the validity of the results compared to field data of the modeled region. The reported research has been successful in reaching this objective, thus confirming the potential use of model abstraction in performance assessment. This result is useful in a general way, but may vary in its utility depending on the actual vadose zone conditions of the modeled site and the nature of the abstraction process.

The consensus scores for this project are shown in Table 2. The score for the overall assessment of this work was found to be satisfactory, a professional work that satisfies research objectives. Comments and conclusions within the evaluation categories are provided below.

Table 2. Summary Results of ACRS Assessment of the Quality of the Project, "Application of Model Abstraction Techniques to Simulate Transport in Soils"

Performance Measures	**Consensus Scores**	**Weights**	**Weighted Scores**
Clarity of presentation	6.0	0.16	0.96
Identification of major assumptions	6.0	0.09	0.54
Justification of major assumptions	5.0	0.12	0.60
Soundness of technical approach/results	6.0	0.52	3.12
Treatment of uncertainties/sensitivities	4.0	0.11	0.44
		Overall Score	**5.7**

Clarity of Presentation (Consensus Score – **6.0**)

The report was well-organized and well-written. The objective of the report was to document results from field studies and related analyses regarding the applicability and efficacy of model abstraction techniques to subsurface flow (of groundwater) and contaminant transport therein. That objective was achieved.

The authors' description of their process (Systematic Model Abstraction and Model Abstraction Steps), Page 11 and their explanation of their actions (context of the modeling problem), Page 12 is thorough and comprehensive. Their presentation and explanation of their data are thorough. The Appendices are appropriate for the document.

In general the report is adequately illustrated, but there are problems with several figures (e.g., several figures lack orientation indicators and distance scales; Figure 3-13 does not have the abscissa identified; and "Well" is not spelled out correctly in Figure 5-2).

An inconsistency exists in the description of the size of the surface of the study area in the Executive Summary. On page xiii, paragraph 4 the size is given as 20 x 20 m; while it is given as 30 x 30 m on page xiv, paragraph 4; and still a different description is given on page 41, paragraph 1.

Some typographical errors exist in the report, e.g., (p)resent on page 1, paragraph 3, line 3. There are also errors in the Symbols section of the report, e.g., aL and aT are both defined as longitudinal dispersivity, aT should be transverse dispersivity; the symbol "R" is used for two items. More specificity could be used in identifying symbols, e.g., ksurf should be more specifically identified as hydraulic conductivity.

Identification of Major Assumptions (Consensus Score – **6.0**)

The nature and validity of the assumptions that are required to implement abstraction modeling are paramount to the abstraction process. The identification of the major assumptions is amply treated in the report. Recognition of these assumptions occurs throughout the report, however, a listing and discussion of them is isolated in Appendix A1.2. This is a useful and comprehensive description of potential assumptions. However, the content of this discussion is central to the application and success of model abstraction. As such it would have been useful to include this discussion together with the background description of model abstraction in Chapter 2.

The report identifies appropriately major assumptions that were utilized for each trial run. Some assumptions are "buried" in the text and the text must be studied in order to understand these assumptions.

It needs to be recognized that there are important assumptions made in the software used in the interpretation and modeling computer programs that have been used in this research study. These assumptions are often buried in the detailed discussion of the software, but could under certain conditions have a significant impact on the results. Generally, these assumptions are taken for granted and not described.

Justification of Major Assumptions (Consensus Score – **5.0**)

The major assumptions pertaining to the abstraction process for the study of site ARS - OPE3 are largely derived from field and laboratory studies obtained from surveys, monitoring, laboratory tests, and hydrologic experiments as described in Section 3.2.2 of the report. They encompass the variety of assumptions identified in Appendix A1.2 that are important to flow modeling of the vadose zone. As a result the report adequately justifies the major assumptions. This is a major element of the research study, and thus is described in detail.

The text provides justification for major assumptions. In some cases, the reader is required to read through a significant amount of text in order to understand the justification of the assumptions.

Soundness of Technical Approach/Results (Consensus Score – **6.0**)

The equipment used in the field and laboratory studies was first rate and well positioned to obtain the best possible data. The experimental procedures that were employed are state-of-the-art and observation protocols were appropriately based on modeling of the anticipated responses. The software used in the analyses is appropriate or modified to achieve the best possible results.

The technical approach and the design of the research study are critical to achieving the objectives of the study. The research plan which included both analytical modeling as well as comprehensive studies involving borehole investigations, electrical resistivity and ground-penetrating radar geophysical surveys, as well as laboratory hydraulic measurements follows a logical and comprehensive process designed to successfully meet the objectives of the research.

Figure 2-4 presents an illustrative diagram of the design of model abstraction via model structure and parametric determination for a generic process. However, this specific study as described in Chapters 3 through 5 is complex. As a result the actual research plan would be more easily understood if a flow chart had been provided that would assist the reader in following the investigation from parametric determination to construction of the base and flow models to verification of the model abstraction.

The researchers did a comprehensive job studying the controlled area. Their practical and persistent actions to understand how the injected fluid (surrogate for contaminant) behaved in the soil and underlying structure is thorough and well done.

Treatment of Uncertainties/Sensitivities (Consensus Score – **4.0**)

Uncertainties in the modeling process and its parameters and sensitivities of the results of modeling to the variability of parameters and processes are central to model abstraction. As a result a great deal of the research effort described in NUREG/CR–7026 involves consideration of uncertainties in the abstraction process and sensitivity studies to evaluate the effect of parameter and model structure variability. Appropriately the Monte Carlo method was used in this research study to investigate the impact of uncertainties on abstracted models using data incorporating the variability of calibrated, measured, or estimated hydrologic parameters.

Sensitivity studies were appropriately a significant part of this research study. For example, they were used to investigate the assumed dissolution rates of the tracers at the soil-surface used in both the solute flux and the lateral flow experiments and the solute transport for a range of longitudinal dispersivities.

The research site used for the study is a 20m x 20m site within the 300m x 300m site. As noted by authors, the 20m x 20m site is a ‘pixel’ in the larger experimental field. The 20m x 20m surface of the study area provided interesting information that adds knowledge to the usefulness of abstraction techniques for “computer” modeling. However, the relevance of data from this small ‘pixel’ of land to a larger land mass, whose underlying geology is unknown, is questionable.

3.2 Fuel Fragmentation, Relocation, and Dispersal during the Loss-of-Coolant Accident

In 2008, the NRC issued a technical basis document [15] for revising the loss-of-coolant accident (LOCA) cladding embrittlement criteria found in Title 10 of the Code of Federal Regulations (10 CFR) 50.46, “Acceptance Criteria for Emergency Core Cooling Systems for Light-Water Nuclear Power Reactors.” This document identified axial fuel relocation and the loss of fuel particles through a rupture opening as areas that needed further research. Subsequently, the NRC staff initiated a study to review historical and more recent data to determine if there are trends or observations that can be used to characterize the likelihood of fuel fragmentation, fuel relocation, and fuel dispersal under LOCA conditions. The results of this study are documented in NUREG-2121, “Fuel Fragmentation, Relocation, and Dispersal during the Loss-of-Coolant Accident” [16]. The report also presents a preliminary assessment of the consequences of fuel fragmentation, relocation, and dispersal. The scope of this quality review is limited to this report.

General Observations

The essence of the report is an examination of past loss-of-coolant tests with reactor fuel. The examination was particularly for evidence of fuel fragmentation, relocation and dispersal from the clad fuel rod. The author has done a heroic job of identifying and retrieving reports on the past experimental efforts. The only omission that could be identified was the work by Lorenz, Collins and Malinauskas on gap release of radionuclides during LOCA excursions [17]. These authors noted in their laboratory reports but not in their archival paper some fuel particle release upon clad rupture and fuel rod venting. They did not include this particulate release in their recommendations concerning radionuclide releases to be associated with LOCA events. They argued that particles were too large to remain airborne for times sufficient to reach the reactor containment.

The purpose of the document is a bit unclear. The purpose is defined at least three times in the report, but it is defined differently each time. Our conclusion is that report fulfills the first of the three objectives of the sponsor of the work:

- Can relocation and dispersal of fuel occur during a LOCA?
- Can the relocation and dispersal be modeled?
- Do the models indicate the phenomena will impact safety?

Since pertinent loss-of-coolant accidents have not occurred in operating reactors, the author of the report had to examine test literature to address the first of these issues. He did so, and we do not at all underestimate the effort it took to find and review this literature for findings that were not the foci of the original reports. Nevertheless, the examination could have been improved substantially had the author guided his examinations with modeling and the current understanding of fuel fragmentation, relocation and dispersal.

The consensus scores for this project are shown in Table 3. The score for the overall assessment of this work was found to be 4.5 (satisfactory, with some limitations, the results meet the research objectives). The members of the review panel agreed collectively to not assess the work with regard to identification and justification of assumptions. The election to omit quantitative assessment of the work with regard to assumptions was based on the dependence of the work on the documentation of legacy experiments. The review panel does note that there are inherent assumptions in the work. In particular there are assumptions about tests adequately representing reactor events and the distortions caused by refabricating of fuel for use in tests. Comments and conclusions within the applicable evaluation categories are provided below.

Table 3. Summary Results of ACRS Assessment of the Quality of the Project, "Fuel Fragmentation, Relocation, and Dispersal during the Loss-of-Coolant Accident"

Performance Measures	Consensus Scores	Weights	Weighted Scores
Clarity of presentation	5.0	0.20	1.0
Identification of major assumptions	NA		
Justification of major assumptions	NA		
Soundness of technical approach/results	5.0	0.66	3.3
Treatment of uncertainties/sensitivities	3.0	0.14	0.42
		Overall Score	**4.7**

Clarity of Presentation (Consensus Score – **5.0**)

Data from the major research projects relevant to the phenomena of fuel fragmentation, axial relocation and dispersal during a loss of coolant accident have been carefully compiled and evaluated. Overall, the report presents a wealth of data which should be of great value to the staff in the evaluation of operating plant issues.

The general structure of the report is good. The depth of detail adopted by the author is appropriate. Specific attention to the definition of terms early in the report is especially helpful. However, some undefined terms crept into the descriptions. Examples are provided in the detailed comments that follow. It was especially disappointing to see that the distinction between fragmentation and fracturing of fuel pellets drawn early in the report was disregarded as the presentation of results progressed.

The summary tabulation of test results was a great idea, and it is clear that the author worked hard to develop these tables. It would have helped readers had the author adequately signaled the existence of these tables as he undertook descriptions of the tests in a separate section. A more serious concern in the presentation of the results is for the test descriptions to be followed by a set of conclusions that include speculations by the author. Speculations should be kept separate from the presentation of factual results.

The author needs to be more careful in his acknowledgement of prior work in the field. He needs to be much more careful especially when reaching conclusions that have been reached in the past by others. Such attentions will help his exposition of his findings.

The main report should reference the Appendix and provide the reader an explanation for why it is included in this report. The main report does not even mention it.

Soundness of Technical Approach/Results (Consensus Score – **5.0**)

The basic approach adopted by the author and the diligence with which he pursued the approach are admirable. He did ferret out obscure laboratory reports and other difficult sources of information and he did try to distill the findings into a tractable report. This was all quite good. The approach was flawed because the author focused entirely on the experimental findings and did not guide his selection of results to report using current understanding and models of the pertinent phenomena. This leads to a failure to report things like fuel porosity and grain size or other microstructural features known to affect fuel fragmentation and relocation. There was no effort to compare test results to current modeling or understanding. Such comparisons are often useful in the identification of experimental 'outliers'. One consequence of the omissions in the approach is that should anyone want to use data compiled in the report to compare to models such as those of Ogama (M. Oguma, "Cracking and Relocation Behavior of Nuclear Fuel Pellets During Rise to Power, Nucl. Eng. Design, 76 (01983)35-45. M. Oguma, "Microstructure Effects on Fracture Strength of UO2 Fuel Pellets, J. Nucl. Sci. Tech. 19 (182) 1005.) or more modern models, they will have to repeat the searches done by the author to find pertinent information.

There is a desultory attempt to identify trends in the observed data. It is not at all clear what strategy the author pursues in this undertaking. (It is not crystal clear the author did this work since it is attributed to 'the staff'.) In particular, the author does not indicate what measure of correlation he was using in making his comparisons. It appears that he may have been using a simple product-moment correlation coefficient. Rank correlation may have been more appropriate for highly scattered data he had available.

This report provides a review, data compilation, and preliminary analysis of eight experimental programs spanning the period from the late 1970s to the present. These programs addressed a number of phenomena occurring in fuel elements during loss of coolant accidents. Many of the research programs reviewed were not focused on fuel fragmentation, relocation and dispersal. In these cases, the author extracted quantitative data on the dimensions of ballooned and ruptured cladding, the extent of axial relocation and the dimensions of fuel fragments from metallographic data presented in the various research reports. The author then tabulated both qualitative observations and quantitative data of these parameters and compiled them along with the main experimental variables in each program into a consistent set of tables. In addition, the author plotted data from the various research programs to illustrate the influence of various design and experimental variables on the extent of fragmentation, relocation and dispersal. The data trends were summarized as follows:

- Fuel fragmentation appears to increase with burnup.

- Rod fill pressure has a direct impact on the balloon and rupture characteristics, such that increased rod fill pressure results in shorter balloons but wider rupture openings.

- Rod fill pressure has a direct impact on rupture pressure and temperature, such that increased fill pressure results in increased rupture pressure and decreased rupture temperature.

- There is a strong inverse correlation between rupture pressure and temperature.

- As expected, the rupture area increases with rupture width and length.

- Balloon length increases if the rupture (i.e., the balloon) is further from the plenum.

It is puzzling why the author chose to emphasize rod fill pressure as an important variable affecting the phenomena of interest, since rod internal pressure (the sum of fill pressure and released fission gas pressure) controls the stress on the cladding during a LOCA event. As presented, the benefits of optimizing the rod fill pressure to reduce fission gas release and rod internal pressure in high burnup fuel is needlessly obscured.

Treatment of Uncertainties/Sensitivities (Consensus Score – **3.0**)

The author makes no disciplined effort to consider uncertainties in the results he describes. In many respects, the author is at the mercy of those that wrote the original reports, so he can only do what the information will allow him to do. But, in fact, he avoids addressing even elementary uncertainties such as uncertainties in parameters and predictions for the correlation of data shown in Figure 4-15. Similarly, he does not acknowledge the problems of uncertainties in sieving analyses that afflict comparisons of results shown in Figure 4-40. More important is the neglect of experimental errors and biases in the experimental results that will affect the extrapolation to reactor accidents. The author may not be able to or even want to apply corrections to the data but he needs to make clear where there are nonprototypical features in the tests. These nonprototypical features should have a visibility equivalent to the summary data shown in section 4.2.1. Certainly, the author should be aware of the strict discipline accorded by the CSAU methodology [18] to uncertainties and biases in test results.

4. REFERENCES

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