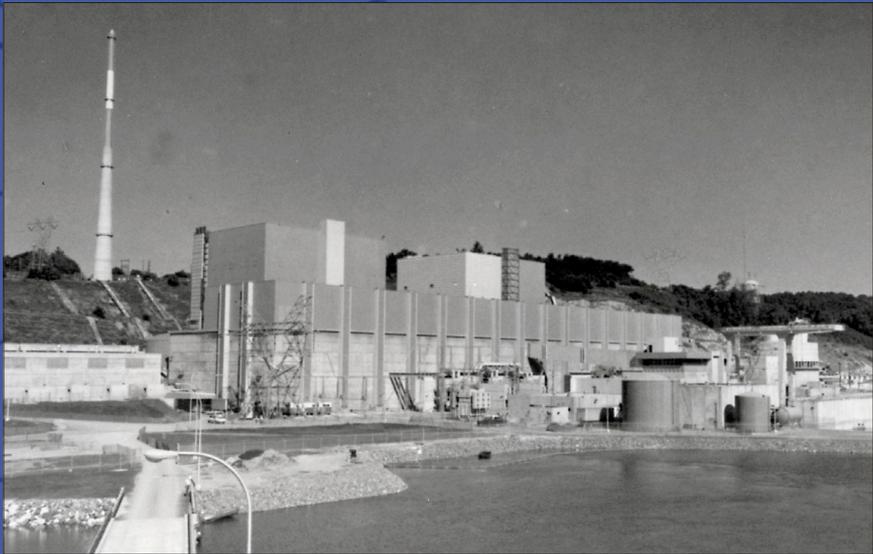




United States Nuclear Regulatory Commission

*Protecting People and the Environment*



# WASH-1400

## The Reactor Safety Study

The Introduction of Risk Assessment to the Regulation of Nuclear Reactors

NUREG/KM-0010

*Peach Bottom Nuclear Power Plant (shown on cover) was studied in WASH-1400.*



NUREG/KM-0010

# **WASH-1400**

## **The Reactor Safety Study**

### **The Introduction of Risk Assessment to the Regulation of Nuclear Reactors**

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Office of Nuclear Reactor Regulation



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# Preface

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This NUREG incorporates information from the November 9, 2015, presentation titled “WASH-1400 and the Origins of Probabilistic Risk Assessment in the Nuclear Industry,” by Drs. Thomas Wellock and Robert Budnitz, at the U.S. Nuclear Regulatory Commission (NRC) Headquarters in Rockville, MD. Felix Gonzalez and Dr. Nathan Siu from the Office of Nuclear Regulatory Research and Christine Steger, a member of the knowledge management staff in the Office of the Chief Human Capital Officer, who had the vision to produce this program in support of the NRC’s Knowledge Management Program. A video of the lecture is available (Agencywide Documents Access and Management System (ADAMS) Accession No. ML15348A211). The intended audience for this NUREG is anyone who has an interest in either the technical topic or the history of the use of risk analysis tools at the NRC. The lecture on November 9 featured both historical knowledge from Dr. Wellock and primary source information from Dr. Budnitz, who participated in the review of WASH-1400 in the mid 1970s. For completeness, the preparer expanded on the material presented on November 9 to ensure sufficient context for readers who may not be familiar with the topic.



# Foreword

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Our responsibility at the U.S. Nuclear Regulatory Commission (NRC) is regulating nuclear power plants to ensure the safe and secure use of nuclear power and nuclear materials. Probabilistic risk assessment is one of our most powerful tools used in developing and implementing risk informed regulations. Ever since the publishing of WASH-1400, probabilistic risk assessment has grown to become a vital part of improving the NRC's efforts in ensuring the safety of nuclear power plants.

WASH-1400 represented a watershed event for the development and use of risk assessment in the nuclear industry. The events documented in this booklet encapsulate the movements surrounding the development of WASH-1400, how WASH-1400 became a proof of concept for the application of risk assessment, and how risk assessment has influenced nuclear power plant safety regulation today.



William Dean  
Director of the Office of Nuclear  
Reactor Regulation



Michael Weber  
Director of the Office of Nuclear  
Regulatory Research



# Acknowledgments

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I am grateful for the assistance on this NUREG from several NRC staff members, listed in no particular order:

- Mr. Greg Casto—For allowing me the opportunity to work on this NUREG and also providing feedback on draft versions.
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2016 Summer College Intern, Florida State University-  
Class of 2017



Dr. Thomas Wellock is the historian for the U.S. Nuclear Regulatory Commission (NRC). Trained as both an engineer and a historian, he writes scholarly histories of the regulation of commercial nuclear energy. Until 2010, he was a Professor in the Department of History at Central Washington University in Ellensburg, WA. He is the author of two books, *Critical Masses: Opposition to Nuclear Power in California, 1958–1978* and *Preserving the Nation: The Conservation and Environmental Movements, 1870–2000*. He has also written many articles on the history of nuclear power. His engineering experience includes work for General Dynamics Corporation as a reactor test engineer in the construction of Los Angeles and Trident class submarines.



Dr. Robert J. Budnitz has worked in the areas of nuclear reactor safety and radioactive waste for many years. He is on the scientific staff at the University of California Lawrence Berkeley National Laboratory, where he focuses on nuclear power safety security and radioactive waste management. From 2002 to 2007, at the University of California Lawrence Livermore National Laboratory, he served a 2-year special assignment in Washington to assist the Director of the Office of Civilian Radioactive Waste Management to develop a new Science & Technology Program. Before joining Lawrence Livermore in 2002, he ran a one-person consulting practice in California for over two decades. From 1978 to 1980, he was a senior official on the staff of the NRC, serving as Deputy Director and then Director of the Office of Nuclear Regulatory Research. In these roles, Dr. Budnitz was responsible for formulating and guiding the large NRC research program. From 1967 to 1978, he was at Lawrence Berkeley, including a stint as the laboratory's Associate Director and Head of the Energy & Environmental Division.

# 1. Introduction

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## *Description of Probabilistic Risk Assessment*

Probabilistic risk assessment (PRA) examines both the probability of an accident and its possible consequences. Today, PRA plays a major role in the U.S. Nuclear Regulatory Commission's (NRC's) regulatory process and in many initiatives that improve the agency's effectiveness. The NRC combines both quantitative probabilities and qualitative engineering judgment in regulating activities. Quantitative and qualitative approaches are both part of what is called "risk-informed, performance-based regulation."<sup>1</sup>

The NRC uses PRA tools to develop the quantified or numerical side of the risk-informed, performance-based regulation. WASH-1400, "Reactor Safety Study," issued October 1975, was the first full-scope use of PRA techniques and contributed greatly to the development of the quantitative side of risk-informed, performance-based regulations.

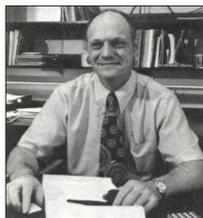
Risk quantification uses the risk triplet<sup>2</sup> as a set of three questions that can be used to define "risk":

1. What can go wrong?
2. How likely is it?
3. What are the consequences?

By examining the proposed scenarios, analysts can identify safety vulnerabilities and determine where best to apply resources to address those vulnerabilities.

<sup>1</sup> See the staff requirements memorandum for SECY-98-144, "White Paper on Risk-Informed and Performance-Based Regulation," dated March 1, 1999, for a more detailed discussion of the current use of risk information at the NRC (Agencywide Documents Access and Management System (ADAMS) Accession No. ML003753601).

<sup>2</sup> John Garrick and Stanley Kaplan first introduced the risk triplet concept in a 1981 article, "On the Quantitative Definition of Risk."



*Norm Rasmussen  
(top) and Saul  
Levine (bottom)  
were instrumental in  
the development of  
WASH-1400*

## ***Overview of Probabilistic Risk Assessment History***

Government, industry, and academic visionaries have long thought it would be useful to have a quantitative, probabilistic representation of the risk associated with nuclear reactor safety. This approach would provide statistical frequencies estimating the probability of an accident occurring. The first U.S. regulator of the nuclear power industry, the Atomic Energy Commission (AEC), greeted early attempts at creating these representations with much skepticism. Nevertheless, the AEC launched WASH-1400 in 1972 under the leadership of Norm Rasmussen at the Massachusetts Institute of Technology (who had previously contracted with the AEC) and AEC member Saul Levine. A team of over 50 contractors and AEC staff worked over 3 years to produce a draft of WASH-1400 in 1974.<sup>3</sup> After Congress transferred authority to regulate nuclear power plants from the AEC to the newly established NRC in 1974,<sup>4</sup> the NRC published the final report in October 1975. WASH-1400 demonstrated that PRA could offer new, important, and actionable insights that benefit reactor safety.

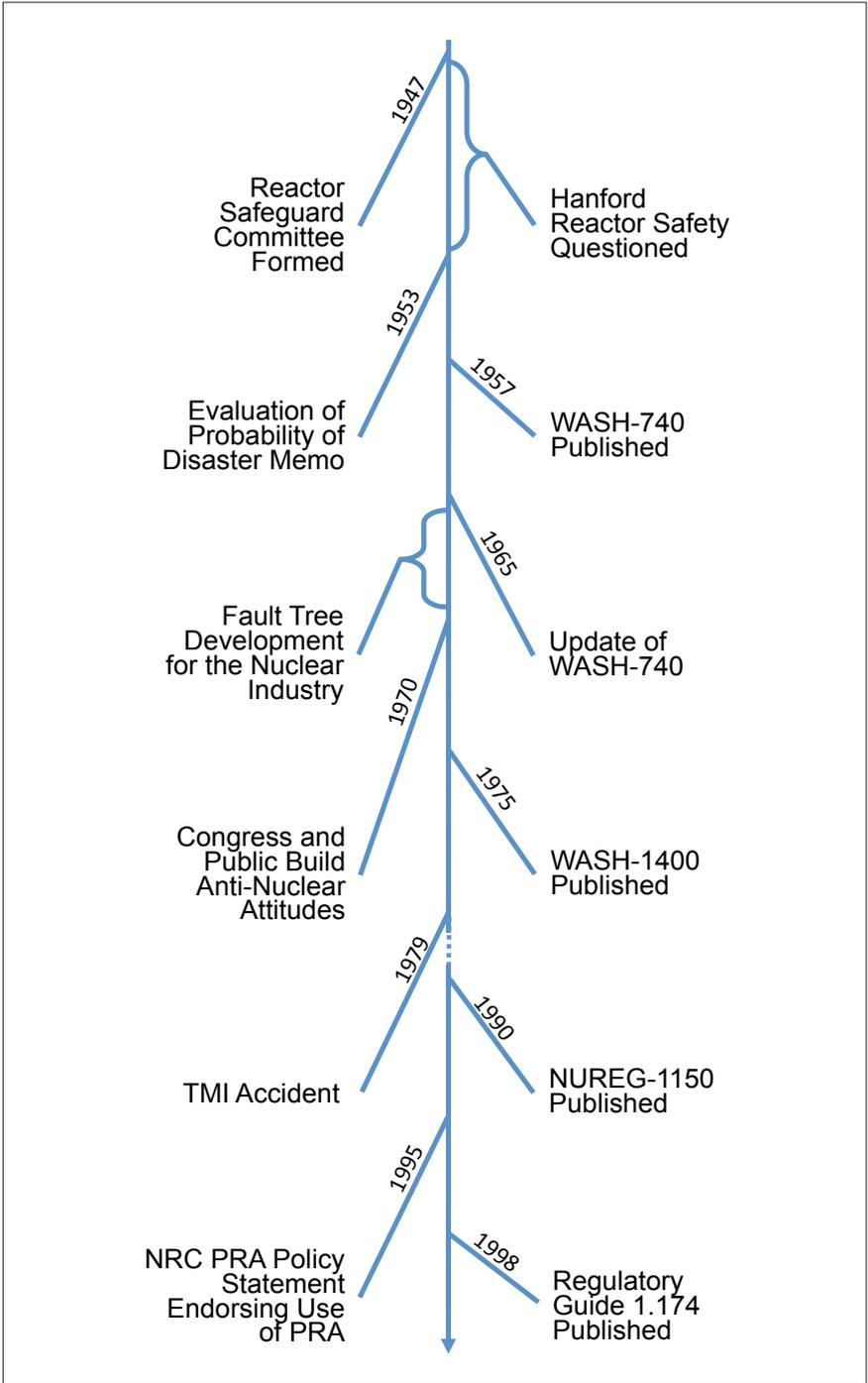
### ***The “P” in Probabilistic Risk Assessment***

Putting the “P” in PRA—working out the probabilities of individual accident sequences and, from those, the overall probability of a major accident—was a goal that had long eluded nuclear experts and provided the motivation for developing WASH-1400. In the late 1940s, the AEC and employees working on weapons production reactors were confident that they could make a realistic ballpark estimate of accident consequences. However, they recognized that methods to quantify accident sequence probabilities produced results that “...weren’t even... in the same solar system,” in Dr.

<sup>3</sup> “WASH” is short for Washington. The AEC used WASH as a prefix for its documents.

<sup>4</sup> See the *Energy Reorganization Act of 1974*.

Wellock's words. This challenge of creating realistic probability estimates with reasonable margins of error led to models focused on probabilities and in turn WASH-1400.



*Events associated with PRA Since 1947*

## 2. The Environment Leading to the Risk Assessment

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### *Licensees and the AEC Preferred Deterministic Design*

Early designers of nuclear reactors could not assure reactor safety through a quantitative, probabilistic approach, and the AEC instead relied on “deterministic” design safety where probabilities were estimated qualitatively through engineering judgment.

Deterministic design relied on design-basis accidents—originally called maximum credible accidents—to ensure plant safety. A reactor designer postulated a number of “credible” plant events that could lead to reactor fuel damage and a major release of radiation. As Dr. Budnitz explained, “A design-basis accident is not an accident at all...[it is] an initiator for an event.”<sup>5</sup> For instance, a loss of offsite power is a design-basis accident, because it is considered a credible initiator of an event that could lead to a series of events with significant consequences. By contrast, a meteor striking the plant was possible but not considered a credible initiator. The AEC required plant designers to consider loss of power and many other credible accidents to “determine” what safety features their design needed. In lieu of any risk assessment, deterministic designs aimed at making the probability of a catastrophic event “incredible.”



*The AEC logo*

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<sup>5</sup> An initiator (e.g., a spark) causes an event (e.g., a fire) that leads to an accident (e.g., release of radiation).

The following are examples of the design-basis accidents listed in Chapter 15 of NUREG-0800, “Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition”:

- major rupture of reactor coolant boundary
- control rod ejection from the reactor
- major rupture of secondary system boundary
- stoppage of major pump within the reactor coolant system

### *Reactor Safeguards Committee*

The deterministic approach dominated the thinking of the earliest reactor safety reviews done after World War II. At this time, the Argonne National Laboratory, a government nuclear research laboratory, wanted to create a nuclear test facility and debated whether to locate it in Chicago or in the desolate fields of Idaho. Brookhaven National Laboratory, another government research laboratory located on Long Island, also planned to build a reactor in the late 1940s, which raised many questions about reactor safety. In 1947, the AEC established the Reactor Safeguards Committee (RSGC) to review the design safety of these proposed reactors.

RSGC was the AEC’s advisory group of independent technical experts that evaluated technical health and safety aspects of reactor hazards. In 1953, the Committee was renamed the Advisory Committee on Reactor Safeguards (ACRS). Congress later established ACRS as a statutory Federal advisory committee (see “ACRS History” on the NRC Web site).

## *The Hanford Problem*



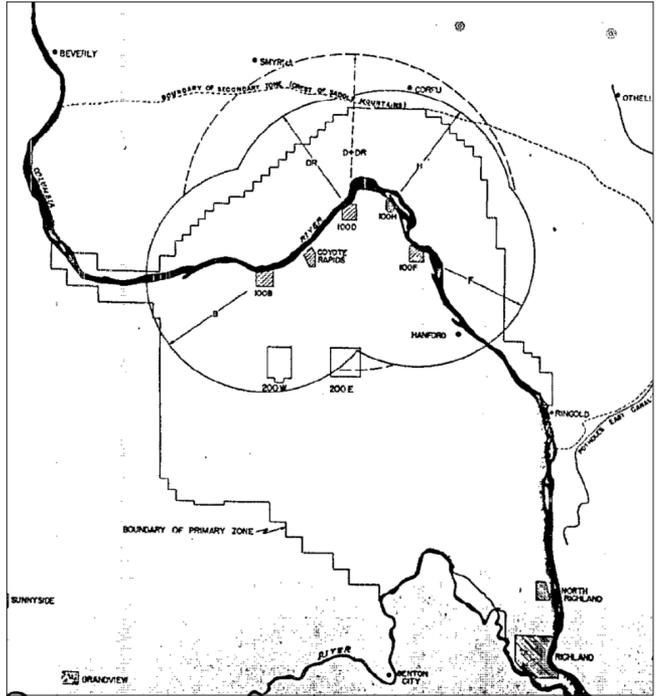
*Hanford Reactor B  
located on the Hanford  
Reservation*

Shortly after RSGC was formed, its members began to worry about the Hanford nuclear weapons production reactors. At the time, the AEC regulated these reactors. The Hanford reactors had developed safety problems not anticipated in the plant's emergency shutdown capabilities. RSGC considered the Hanford reactors the least safe of all AEC reactors. During this time, physicist Edward Teller led RSGC with a conservative approach to reactor safety. Teller and his committee proposed a plant isolation formula that stated:

$$\text{Exclusion Area (miles)} = .01\sqrt{\text{Plant Power (kW)}}$$

*(As an application of this rule, the 250 megawatt (2.5x10<sup>5</sup> kilowatt) Hanford B reactor required an 8-kilometer (5-mile) exclusion area.)*

*Hanford reactors with exclusion area (solid circular lines) radially applied to reactors (shaded gray boxes) exceeding Hanford borders (stair-stepped solid lines)*



The formula, as one AEC veteran recalled, was “very conservative and, for reactors now operating, very unrealistic.” RSGC argued that ignorance made such conservatism necessary: “In our present state of knowledge, we cannot possibly recommend settlement of population closer to a pile [reactor] than this distance.”

This equation quickly became unworkable, even for the heavily isolated Hanford Reservation. RSGC realized that it would need to find a better solution than simple isolation and began to pressure Hanford’s contractor, General Electric (GE),<sup>6</sup> to find this solution.

<sup>6</sup> The Federal Government controlled the Hanford site, but contractors operated the site. Although the DuPont Company had constructed the site, at the time this concern was raised, GE had assumed site management.

## *The Search for Reassurance*

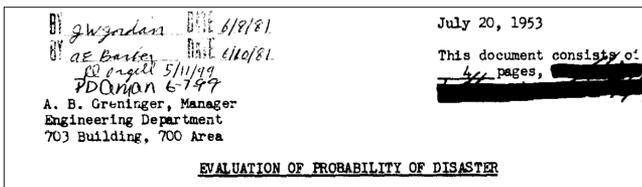
Once the Hanford reactors were found to exceed the RSGC exclusion area formula, RSGC looked to other engineering solutions for reassurance of plant safety. RSGC asked GE to create “foolproof” safety devices, but GE never found such devices. Both parties were in a stalemate regarding the operation of the Hanford reactors. The Hanford reactors were essential because of their production of plutonium during the Cold War, but RSGC still needed some assurance of safety.



### 3. The Beginning of Quantification

#### *The First Attempt at a Probabilistic Approach*

In 1953, GE Hanford’s statistics director submitted a memorandum titled “The Evaluation of Probability of Disaster.” The director proposed a probabilistic plan for safety assurance. The memorandum talked about a “chain of events” that was the culmination of small malfunctions and mistakes that would lead to a disaster. The memorandum reasoned that all the events in the chain leading to a disaster could be examined individually. After these results were evaluated, they would be combined to obtain the probability of an event.



*The “Evaluation of Probability of Disaster” memorandum heading*

#### *Result of the GE-Led Research*

Eight months after submitting the memorandum, GE realized that it could not obtain realistic representations of accident probabilities. GE had difficulty imagining all the possible paths to failure, and the formatting of the failure data used did not interface well with the statistical approach used for generating the probabilities. The collaboration between technical staff at GE also presented a problem—the statisticians did not know the reactors, and the engineers did not know the statistics. The time line on the next page summarizes the key events related to PRA.

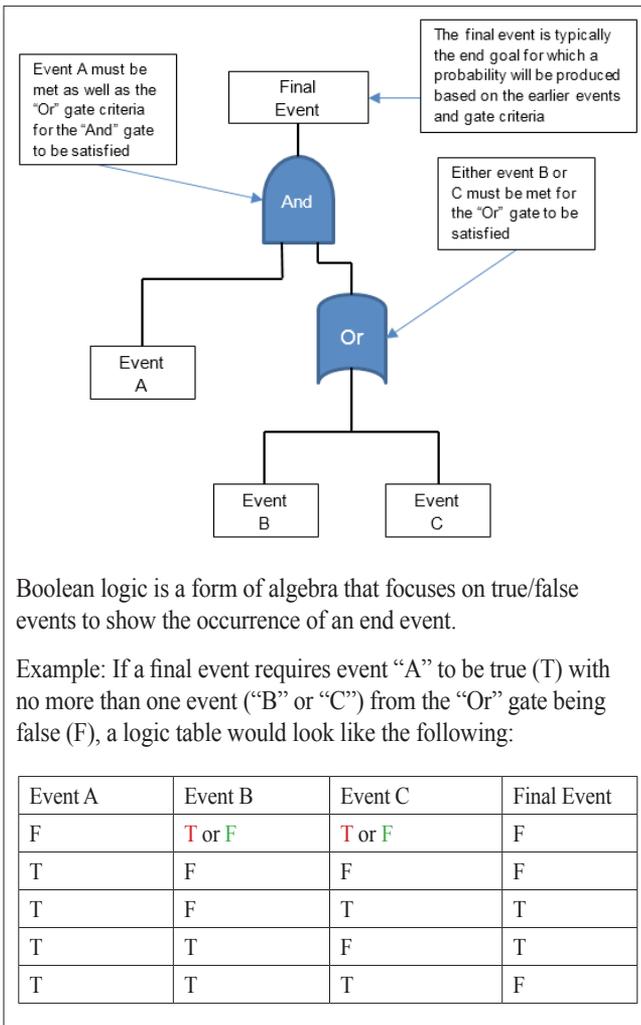
## *GE Finds Inspiration*

Even though GE initially failed at generating probabilities related to reactor accidents, it continued to develop a better understanding of the probabilities for components and systems to fail. GE hoped that it could eventually put all the pieces together and create a comprehensive probabilistic model.

Despite these efforts, in 1964, GE staff admitted that its considerable efforts to create a failure model were unsuccessful. Nevertheless, the company remained a primary pursuer of reliability performance and probability statistics. In the late 1960s, GE began to advocate in political arenas for greater vigor in pursuing probabilistic methods for civilian reactor safety regulation. GE and other nuclear industry firms became interested in fault trees, which had been recently used in the Minuteman missile development program. Fault trees “are clearly something that develops out of the aerospace, airlines industry,” as Dr. Wellock stated in his presentation. The use of fault trees in other industries generated much interest in developing the approach and applying it to specific problems in the nuclear industry.

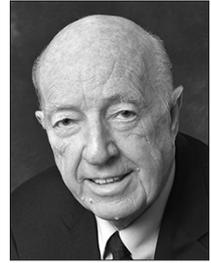
## Fault Trees

In the 1960s, the nuclear industry began applying fault trees to solve engineering problems arising from earthquakes. The AEC began funding studies to improve data collection and fault tree methodology. Fault trees used Boolean logic which encompassed the probability, priority, and criteria of each individual event to find the probability of some final event. General fault tree knowledge and Boolean logic concepts are shown below.





While the fault tree approach was becoming popular, John Garrick completed his Ph.D. dissertation at the University of California Los Angeles based on his work for the AEC contractor, Holmes & Narver. He developed a fairly sophisticated fault tree approach specifically for a nuclear reactor. Dr. Garrick’s fault tree is an example of the state of the art beginning to move forward with the development of methodologies that GE did not have in the 1950s. An example of Garrick’s fault trees (on page 18) shows what Dr. Wellock called “a fairly sophisticated fault tree approach for that time.”



*John Garrick*

### *Fault Tree Usage in Other Industries*

Other early industry applications of fault trees resulted in frustration similar to that experienced by the nuclear industry. The National Aeronautics and Space Administration (NASA) adopted fault tree technology in the 1960s. NASA’s effort suffered the same fate as that of the nuclear industry—its fault trees had numbers with major uncertainties, which left looming questions on fault tree applicability. NASA eventually began to back away from fault tree use around the time the nuclear industry started to incorporate the methodology. This timing gave antinuclear critics what they considered to be a compelling argument against the validity of the statistics in nuclear safety reports.

### ***The AEC’s Skepticism on Risk***

Even as the AEC supported research to improve quantitative approaches to reliability and risk assessments, its regulatory staff was reluctant to accept the idea that probability analysis had matured enough to evaluate quantitative risk for reactors. For example, Stephen H. Hanauer, an AEC technical advisor, wrote a letter that indicated his doubts about the techniques used to find probabilities:



*Stephen H. Hanauer*

*We at the AEC have not yet arrived at the point where probability analysis techniques give adequate assurance that failure modes are indeed considered adequate. That probabilistic models for severe accidents that correspond to actual failures will occur as predicted,*

*and that we are also skeptical that adequate failure rate data are available for prediction.*

Hanauer's letter expressed a common sentiment shared by regulators about probabilistic work during its infancy and was particularly striking because, as Dr. Wellock observed, "He was one of the leading intellectual lights on the regulatory side in the 1960s and early 1970s."

### ***WASH-740—An Early Risk Effort***

The regulatory staff's skepticism about risk assessment came from hard experience. Its early studies, such as WASH-740, "Theoretical Possibilities and Consequences of Major Accidents in Large Nuclear Power Plants," issued March 1957, had produced more frustration than useful information. Also known as "The Brookhaven Report," WASH-740 was the first substantial report on the consequences of a major accident at civilian reactors. It produced alarmingly high consequences for a worst-case accident scenario, but it was unable to put the accident in context with realistic probability estimates since there was no methodology to do so. In the report, the AEC confessed that the best it could provide were engineering estimates of accident probabilities based on expert judgment. Dr. Wellock noted that the authors of WASH-740 admitted "that they had talked to some experts who absolutely refused to give a number because it would give credence to the whole idea that you could come up with a number." Such probabilities, these experts believed, were "unknowable." WASH-740 provided fodder for nuclear critics, but no reassurance. Overturning its results became a longstanding goal of nuclear power advocates.

## *The 1965 Update of WASH-740*

In 1964, the U.S. Congress called on Frank Pittman (the head of reactor research for the AEC) regarding the WASH-740 report. The Joint Committee on Atomic Energy (JCAE) asked Pittman if it was time to revise WASH-740. Pittman explained that there was still not enough research to produce a different result. Any update to the report would have to use the same methods and data, but with larger reactors, the results might show even larger consequences than the original report. JCAE was not satisfied. Two months after the congressional hearing, a JCAE member reasoned that new containment buildings and safety systems added to new reactors would produce a favorable answer in an update. However, the AEC update quickly proved Pittman right. Consequences were much worse. Stuck with a report containing bad news, the AEC considered using probabilities to put the consequence estimates in context.

## *Another Attempt at a Probabilistic Approach*

In an attempt to fix the 1965 update, the AEC contracted with Research Planning Corporation in California to create realistic probability estimates for a severe reactor accident. The results were disappointing. While Research Planning's calculations were good, they were underestimates. Research Planning estimated the probability of a catastrophic accident to be between  $10^{-8}$  to  $10^{-16}$  occurrences per year. If the  $10^{-6}$  estimate were true, that would mean a reactor might operate 700,000 times longer than the currently assumed age of the universe before experiencing a major accident. The numbers were impossibly optimistic, and the error band was distressingly large. As Dr. Wellock recalled, "the AEC wisely looked at this and recognized that probabilities were not going to solve [the problems with] this report." At this time, the AEC understood that

the large error in the obtained probabilities could be attributed to the uncertainty in estimating common-cause accidents.<sup>7</sup>

### *The 1965 Update to WASH-740 Goes Unpublished*

The AEC decided not to publish the 1965 update given its flaws and potential public relations impact. The AEC reported back to JCAE and explained that its preliminary work showed that the consequences grew larger because of the increase in new plants' power production. The results of the 1965 report once again left the AEC uneasy about using probabilities for the assurance of reactor safety.

### *The Antinuclear Movement*

By the late 1960s, the AEC was coming under increased criticism from the antinuclear movement. At the local level, opposition to new plant construction began to build. Nationally, critics questioned whether a key safety system, the emergency core cooling system, would work as designed, which led to a contentious 1972 rulemaking hearing on its safety.<sup>8</sup> Two prominent AEC scientists who worked at Lawrence Livermore National Laboratory, Dr. John Gofman and Dr. Arthur R. Tamplin, raised another safety concern. These scientists claimed that low-level radioactive emissions had greater health effects than the AEC admitted. The AEC also came under scrutiny by other Federal agencies, such as the

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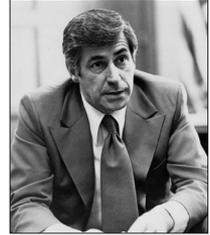
<sup>7</sup> A common-cause (or common-mode) accident is an incidence involving multiple failures that are not statistically independent. An example of a common-cause failure would be a pair of pumps that failed because both were incorrectly maintained. If the pumps both failed for the same reason, the failures would not constitute independent occurrences.

<sup>8</sup> See NUREG/BR-0175, "A Short History of Nuclear Regulation, 1946–2009," Rev. 2, dated October 31, 2010, by J. Samuel Walker and Thomas R. Wellock, ADAMS Accession No. ML102980443, beginning on page 31, "The Problem of Core Melt-down."

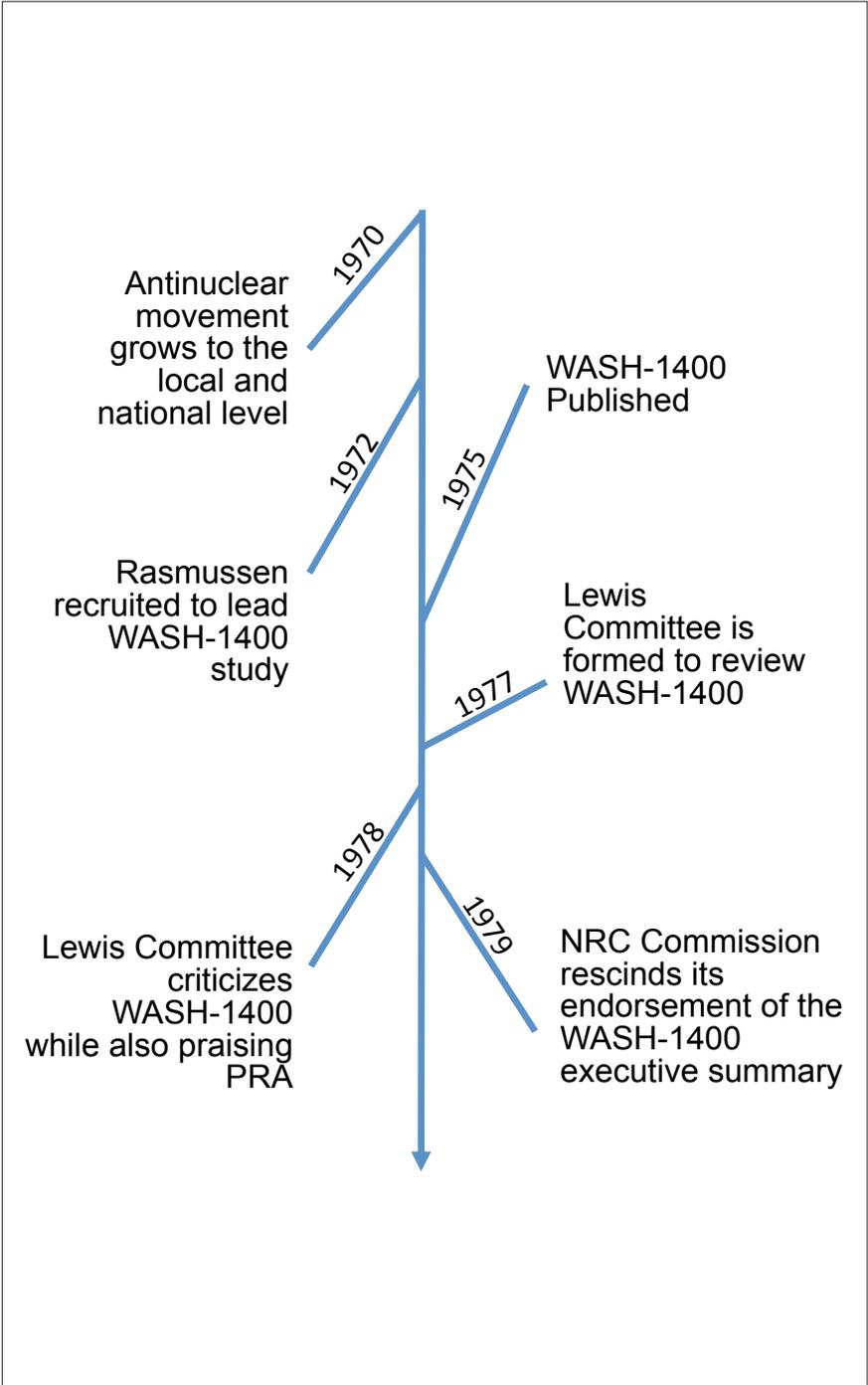
U.S. Environmental Protection Agency. In 1970, the National Environmental Policy Act led the AEC down the path of having to estimate the impact of reactor incidents on the environment.

### ***Congress and the Antinuclear Movement***

As the antinuclear movement percolated, a similar sentiment began to find its way into Congress. Alaskan Senator Mike Gravel criticized the AEC for testing thermonuclear devices on Amchitka Island in the Aleutian Islands chain. Senator Gravel quickly began criticizing atomic energy and became closely associated with the antinuclear movement. As Dr. Wellock pointed out, “He was already critical along those lines [about the thermonuclear device testing]. Picking up criticism of atomic energy wasn’t that hard for him.” Senator Gravel’s criticism quickly turned into skepticism when in 1970 he asked the AEC to show him the 1965 WASH-740 update. Senator Gravel’s request put the AEC in a precarious position because of the problems with the WASH-740 update and the AEC’s subsequent refusal to release the report to antinuclear activists.



*Senator Gravel*



*Events Associated with WASH-1400*

## 4. Development of WASH-1400 Begins

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### *Senator Gravel Forces a New Study*

Despite Senator Gravel’s lack of seniority in Congress, the AEC realized that his request to see the 1965 update must be answered. Dr. Wellock noted, “This is before the age of FOIA,<sup>9</sup> but you don’t easily say no to a senator, even though in this case he was just a junior senator.” The AEC refused to release the report, but it committed to developing a new study. Interest in a new study soon spread to other members of Congress with pronuclear leanings. In 1972, AEC member Saul Levine accepted a temporary assignment with JCAE. Levine quickly read the mood of the Joint Committee, which was now vulnerable to challenges to its authority over nuclear power from the growing environmental movement. Levine suggested that JCAE take charge of the issue by requesting that the AEC launch a new study that laid out its safety approach and dealt with accident consequences and probabilities.

### *Levine Lays the Groundwork*

Levine’s recommendation came a few months after the AEC had already decided it would launch a new study. JCAE liked what Levine proposed, and this gave impetus to the AEC regulatory staff to launch a study on a much larger scale than any previous effort.

### *The AEC Begins Recruiting*

To provide the study with some independence, the AEC looked outside the agency for an expert to lead it, but progress lagged throughout 1971. In early 1972, Stephen Hanauer recruited Norman C. Rasmussen, a nuclear

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<sup>9</sup> The Freedom of Information Act (FOIA) is a Federal statute that allows individuals to request access to Federal agency records.

engineering professor at MIT. Hanauer and Rasmussen laid out the basic components of the study, which included the traditional accident consequence estimates of previous studies, but also added probability estimates derived from fault trees. Because of questions regarding data sufficiency, Rasmussen warned Hanauer that there might be a significant lack of accuracy in their results. Hanauer noted that they might have to learn by trying, a common kind of thinking in 1972.

### ***WASH-1400 Development and Initial Findings***

As Dr. Budnitz stated in the lecture, the goal of the WASH-1400 team was “to identify every single accident sequence that matters and...its probability” and “work out the consequences...being core damage or some release into the containment or some release from the containment...offsite.”

The safety community did not think that such an analysis was possible. It had no confidence that all the probabilities could be worked out, because it thought supporting data were lacking. Despite this doubt, the WASH-1400 analysis group still managed to demonstrate that an accident safety analysis was possible. The analysis group compared nuclear reactor safety with other disasters such as earthquakes, hurricanes, tornadoes, and airline accidents.

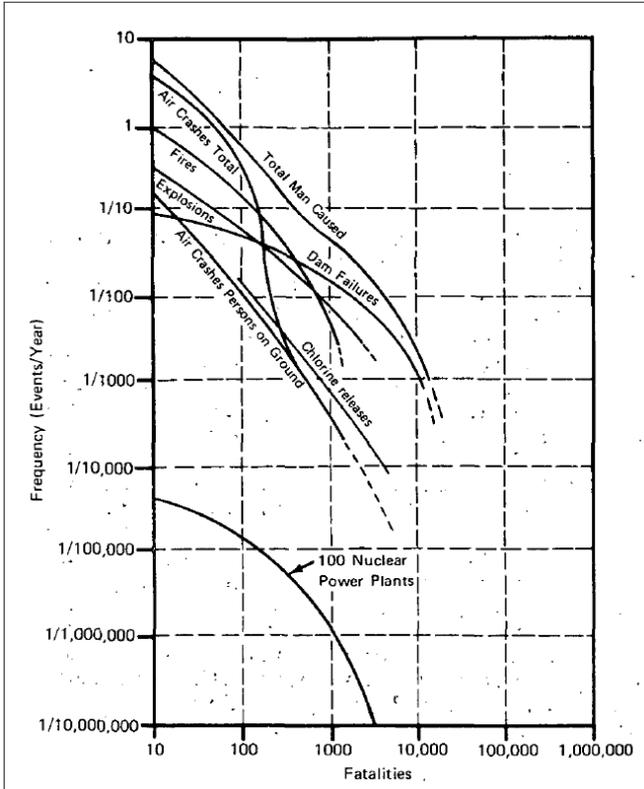


*Dixy Lee Ray with her two dogs*

By 1974, Dixy Lee Ray, then Chairman of the AEC, went before Congress to provide the first estimates from WASH-1400. Ray attempted to put the estimates in a positive, understandable light by using easily understood comparisons to other very unlikely events. She compared the likelihood of a major accident with that of drawing four of a kind in draw poker, twice. The use of these clever comparisons continued throughout the review and into the current era as a way to help the public grasp the safety of nuclear power

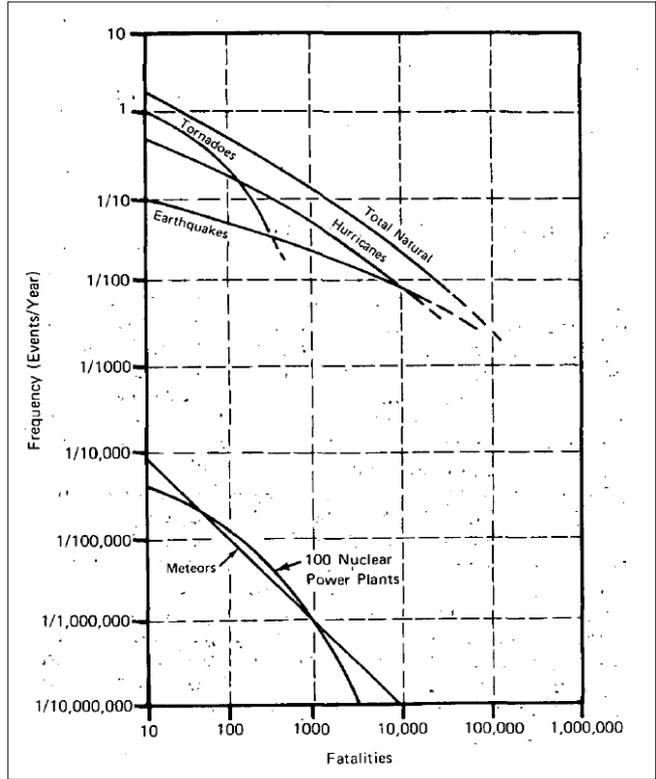
plants. However, some criticized these comparisons as inappropriate given the large uncertainties in the WASH-1400 probability estimates compared to the far more certain probabilities of poker hands, airplane crashes, and lighting strikes.

The next two pages show graphs from the executive summary of WASH-1400.



*WASH-1400 results comparing nuclear power plants and man-made events*

*WASH-1400 results  
comparing nuclear  
power plants and  
natural events*



### ***Realism in WASH-1400***

The analysis group attempted to use realistic frequencies, failure modes, and human error rates in WASH-1400. In the airborne analysis, Robert Ritzman and Richard Denning at Battelle Columbus Laboratories used a realistic understanding of chemistry, physics of aerosols, and airborne contaminants in containment. The offsite dose analysis led by Ian Wall attempted to use realistic analysis of radiological dispersion in the environment, realistic settling velocities, and realistic uptakes in the human body.

Dr. Budnitz offered his insight on the realism in WASH-1400:

*They did everything they could to make [WASH-1400] as realistic as they could. In retrospect they did a pretty*

*good job, although in some places they had a lot of judgment [errors] and didn't get it all right...but it was intended to be, and in retrospect was, realistic.*

### ***Antinuclear Attitudes after WASH-1400***

Accusations of a pronuclear bias at the NRC had also been commonly directed at the AEC. Congress abolished the AEC in 1974 because of the agency's conflicting promotional and regulatory duties and formed the NRC to handle the regulatory issues that were essential to protecting public health and safety. Despite the formation of the NRC in 1975, antinuclear attitudes persisted after the release of WASH-1400. A common sentiment in the antinuclear community was that WASH-1400 was written with the intention of being pronuclear. Later criticism from a review group called the "Lewis Committee" would back up these claims.

Dr. Budnitz summarized the Lewis Committee findings on WASH-1400:

*...[The Lewis Committee] also was very blunt about how although the methods were terrific [in WASH-1400] and the insights were important, the executive summary was way overstating what you could get from this. Crucially, they studied only two reactors...Way overstated it...Also [the Lewis Committee] also said that although they struggled to estimate uncertainties in the study, they had underestimated them by a good deal.*

### ***Initial Regulatory Application of WASH-1400***

After his effort to garner support for the creation of WASH-1400, Saul Levine quickly used the report to analyze the regulations in place in 1975. Levine noted that there were discrepancies in the current regulations, with some aspects being overly stringent and others being inadequate, such as reactor outage requirements.



## 5. The Impact of WASH-1400

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### *The Lewis Committee*

By 1976, Saul Levine had become the Director of Research for the NRC. With his knowledge of WASH-1400, Levine attempted to launch studies aimed at remedying the inadequacies in the report by collecting more information and performing more experiments. At this time, the NRC's Office of Nuclear Regulatory Research had considerable freedom to decide what research projects to undertake, which allowed Levine to pursue research related to WASH-1400.

On March 14, 1977, U.S. Representative Morris Udall, Chairman of the Committee on Interior and Insular Affairs of the U.S. House of Representatives, conducted hearings on the final WASH-1400 report. Representative Udall communicated to the NRC Chairman that there was "widespread belief" that WASH-1400 "was presented in a manner which created a misleading impression of the certainty and comprehensiveness of its conclusions." Representative Udall asked that an independent group develop a new summary to correct this impression.

On April 4, 1977, a letter from the NRC Chairman Marcus Rowden to Representative Udall redirected Udall's request from the development of a new summary to a technical peer review. To this end, the NRC assembled a panel of seven experts to review WASH-1400. The group became known as the "Lewis Committee" and the report as the "Lewis report." The experts spent a year on the report and "basically heard from everybody," as Dr. Budnitz, a member of the group, recalled. The group focused on understanding WASH-1400 and its applicability to nuclear power plant regulation, as well as scrutinizing the models used.

## *The Lewis Report*

In September 1978, the Risk Assessment Review Group, chaired by Hal Lewis, a professor of physics at the University of California, Santa Barbara, published its review of WASH-1400 in NUREG/CR-0400, “Risk Assessment Review Group Report to the U.S. Nuclear Regulatory Commission.” The Committee’s charter stated the following:

*The Review Group will provide an advice and information final report of the Reactor Safety Study, WASH-1400.... This advice and information will assist the Commission in establishing policy regarding the use of risk assessment in the regulatory process, in improving the basis for the use of such assessments. It will also clarify the achievements and limitations of the Reactor Safety Study.*

The highly technical review by the Lewis Committee strongly endorsed the use of PRA methods in regulation in its review, “Risk Assessment Review Group Report to the U. S. Nuclear Regulatory Commission,” page VII:

*WASH-1400 was largely successful in at least three ways: in making the study of reactor safety more rational, in establishing the topology of many accident sequences, and in delineating procedures through which quantitative estimates of the risk can be derived for those sequences for which a data base exists.*

The Lewis Committee praised the usefulness of fault trees. However, while praising WASH-1400, the Committee also criticized the overly optimistic executive summary, which overstated the implications of the main report.

The issues the Lewis Committee found in WASH-1400 included the following:

- The accuracy of the weather (dispersion) model was suspect.
- Unrealistic evacuation schemes were overly optimistic and could have led to a favorably lower fatality rate.
- Earthquakes, fires, and human error were not considered appropriately when determining overall risk.
- Accidents were considered only for the case of the plant running at full power.

Crucially, the Lewis report also noted the significance of the findings in WASH-1400 and how certain regulations were inadequately researched related to “transients, small loss of coolant accidents and human errors” (NUREG/CR-0400, page viii). Dr. Budnitz recounted that the WASH-1400 analysis group “identified for the first time...that small [loss-of-coolant accidents] were really much more important than people had thought.” This finding about small loss-of-coolant accidents (LOCAs) would be important in investigations of the Three Mile Island accident.

Dr. Budnitz commented on the completeness of the WASH-1400 study:

*If you look back now 40 years later, there are not important [accident sequences] that [WASH-1400] didn't capture. They worked out the frequency of every one of those using [fault tree] techniques. The frequencies are more or less right.... When you look back at the places where they didn't get it right [it was] because there weren't enough data or not enough experiments.... It's a tour de force, a major intellectual accomplishment.*

## *Results of the Lewis Report*

After the Lewis report spelled out the deficiencies in WASH-1400, the Commission began to second guess its initial acceptance of the report. One particularly important point that Dr. Lewis made to the Commission, in a NRC Commission briefing in early 1979, was that the uncertainties in the report were so large that “I can’t say anything [about civilian reactors] that would be useful. I can’t learn anything from WASH-1400 that would help me on it.” Because of the increasingly negative atmosphere surrounding WASH-1400 and its executive summary, the Commission, as Dr. Budnitz put it, “bailed” on its total acceptance of the WASH-1400 report in January 1979. However, although the Commission rescinded its endorsement of the report’s executive summary, its policy statement noted that WASH-1400 offered important insights.

The Commission’s statement on WASH-1400 included the following:

- The executive summary does not adequately indicate the full extent of the consequences of reactor accidents and does not sufficiently emphasize the uncertainties involved in the calculations of their probability.
- The peer review process was inadequate.
- Absolute values of risks should not be used uncritically.

In response to the Commission’s statement, press coverage featured headlines such as those in January 20th, 1979 editions of *The Washington Post*, “‘75 Report on Reactor Safety Is Called Unreliable by NRC,” and *The New York Times*, “Nuclear Agency Revokes Support for Safety Study.” Despite the Commission and the public discrediting PRA use, Saul Levine began efforts to fill in the gaps in WASH-1400. The Commission’s criticism of WASH-1400 led to the Office

of Nuclear Regulatory Research launching more studies to remedy the inadequacies of the report. Because of the Three Mile Island incident, most of the studies began just 2 months after the Commission's decision to rescind its endorsement of WASH-1400.

Earthquake accident research began in the Seismic Safety Margins Research Program at Lawrence Livermore National Laboratory, which developed the methodology for seismic PRA. A study of human reliability and error rates and a fire PRA study began at Sandia National Laboratories.

In addition to all the new studies, analysts began using computers to collect and study the data needed to make more accurate models.

Industry stakeholders, represented by the Electric Power Research Institute, launched a study on human reliability analysis. The Germans also launched a study like WASH-1400 at the Biblis Nuclear Plant, under Adolf Birkhofer called "German Risk Study for Nuclear Power Plants." The Biblis study used techniques similar to those used in WASH-1400 and found similar results.

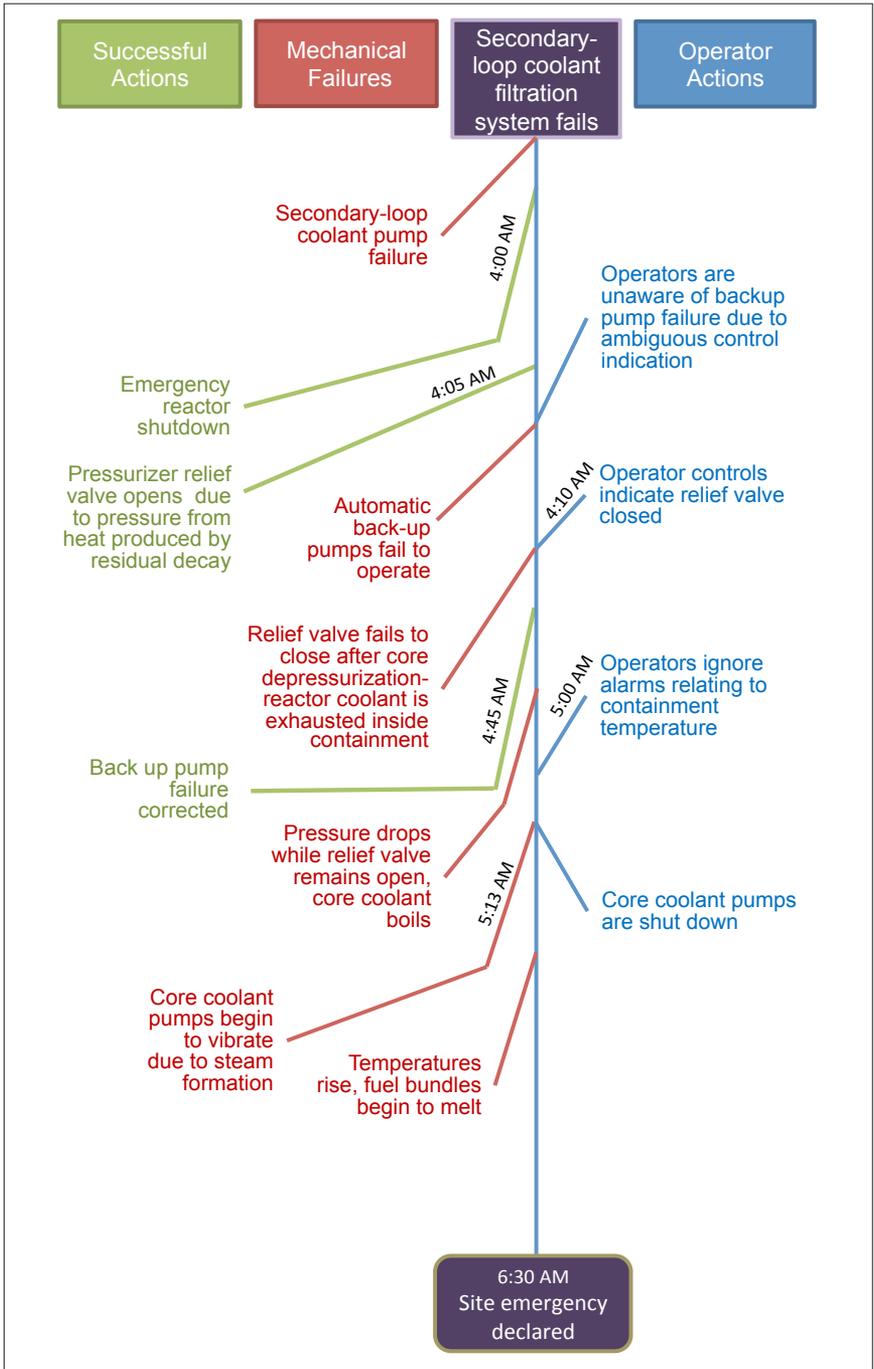
### ***Balance in WASH-1400***

WASH-1400 identified sequences, such as small LOCAs, that continue to be considered important. Another important sequence identified was a loss of offsite power and station blackout. It would take the NRC until 1988 to promulgate a rule, Title 10 of the Code of Federal Regulations (10 CFR) 50.63, "Loss of All Alternating Current Power," to address station blackout.

WASH-1400 also identified some sequences as less important to risk than previously considered. For example, large LOCAs, the ultimate in design-basis accidents, were not as important as people had thought.

Another example of balance is that WASH-1400 estimated the frequency of an accident to be higher than previously expected, but the consequences of most accidents to be smaller than many people had thought. Dr. Budnitz noted that “The antinuclear people thought [WASH-1400] couldn’t possibly be right because they had been telling themselves that every core damage accident was going to contaminate an area the size of the State of Pennsylvania [due to the WASH-740 update report by Brookhaven National Laboratory].”





*Three-Mile Island Accident Timeline  
March 24, 1979*

## 6. Three Mile Island

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### *Background*

On March 28, 1979, an accident occurred at the Unit 2 reactor at the Three Mile Island Nuclear Generating Station (TMI) in Dauphin County, PA. TMI Unit 2 partially melted down because of a small LOCA resulting from a combination of human factors and mechanical failure. While the incident did not result in a significant offsite dose to the public, the accident at TMI Unit 2 represented a major turning point for the nuclear industry in the United States and internationally.



*Three Mile Island*

### *Loss-of-Coolant Accident*

One major accident of concern in nuclear power plant safety is a LOCA. In a general sense, a LOCA is any accident where the liquid used to cool a reactor core is lost. At TMI Unit 2, the regular equipment used to recirculate and pump water through the secondary cooling system failed, which was an initiating event for the plant's eventual LOCA. After the coolant recirculating equipment failed, auxiliary pumps were brought on line in lieu of the properly working equipment. The auxiliary pumps did not function because of problems with an unauthorized

maintenance procedure. The next fail-safe in place was a pilotoperated relief valve designed to vent excess steam being produced inside the reactor because of the lack of a cool water supply. This valve properly actuated initially and relieved the vessel of pressure, but it did not properly reset into a closed position.

### ***Operator Actions and Human Reliability Analysis***

Operator error and poor instrumentation design did not alert reactor employees of a malfunctioning pilotoperated relief valve (a valve located at the top of the pressurizer). The malfunction allowed the relief valve to remain open while coolant was lost. After a series of further errors caused by the ambiguous control panel indications, the reactor core fuel began to melt. With the reactor's pilot-operated relief valve still open, radioactive gasses were vented and eventually escaped into the containment building. The operators took further action once they realized the valve malfunction. The role of human error in the TMI Unit 2 accident would motivate future studies of human reliability and error risk analysis.

### ***WASH-1400 and Loss-of-Coolant Accidents***

One of the findings of WASH-1400 that would anticipate the events at TMI was the importance of small-break LOCAs compared to that of large-break LOCAs. Before WASH-1400, much of the effort to ensure reactor safety focused on large-break LOCAs. In a large-break LOCA, a large amount of coolant is promptly lost from the reactor, which creates a low pressure inside the reactor vessel and associated piping. Automatic safety systems can deal with large-break LOCAs by using low-pressure, high-volume pumps to keep water covering and cooling the reactor core. In a small-break LOCA, coolant is

lost at a lower rate than in a large-break LOCA, but the reactor vessel still maintains high pressures. Operators can deal with small-break LOCAs by using high-pressure, low-volume pumps to cover and cool the reactor core.

### ***WASH-1400 and Three Mile Island***

The accident at TMI is an example of a small-break LOCA. While WASH-1400 did not predict the exact accident sequence that occurred at TMI, it did correctly identify that a small-break LOCA could initiate core damage. Although the TMI accident involved a pressurized-water reactor, it is not the same type of reactor analyzed in WASH-1400. The report analyzed Surry Nuclear Power Station, which had a Westinghouse reactor, whereas TMI had a Babcock & Wilcox design. While Surry and TMI both had pressurized-water reactors, the accident sequences cannot be directly compared because of the difference in design of the steam generators.

The WASH-1400 PRA for Surry did not identify a sequence in which the operators turned off the pumps that they needed because an operator misread a meter. The big-picture failures were similar, but WASH-1400 did not identify the specific failure sequence at TMI. However, WASH-1400 did predict that severe core damage would be contained. The controlled releases from the containment building to reduce pressure did let out some radiation from TMI, but melted fuel did not escape the reactor vessel, which could have created a much more severe situation. In this way, WASH-1400 did prove prescient concerning the TMI accident outcome. The follow page identifies key events related to the TMI accident.



## 7. After WASH-1400 and Three Mile Island

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### *Regulations after Three Mile Island*

Shortly after the TMI accident, the nuclear industry launched a study called “The Industry Degraded Core Rulemaking” (IDCOR) in 1981 with the goal of better understanding severe accident phenomenology. By 1984, IDCOR came to three primary conclusions in an effort to prevent rulemaking for severe accidents:

1. The probabilities of severe nuclear accidents occurring are extremely low.
2. The fission product source terms—quantities and types of radioactive material released in the event of severe accidents—are likely to be much less than previous studies had calculated.
3. The risks and consequences to the public of severe nuclear accidents are significantly less than those predicted by previous studies and much smaller than the risk levels incorporated in the NRC interim safety goals.

The IDCOR program was an early adoption of PRA by the nuclear industry and concurred with WASH-1400 on the safety of nuclear power plants.

### *Additional Probabilistic Risk Assessment Efforts*

WASH-1400 studied only “internal” events at full plant power. Subsequently, industry and NRC studies began to include external events, as well as risks associated with plants running at conditions other than full power. PRA related to fire has been of much interest. On March 22, 1975, a fire at the Browns Ferry Nuclear Power Plant fundamentally changed how the NRC dealt with fire protection at U.S. nuclear power plants. By the

time firefighters extinguished the fire, it had burned for 7 hours. More than 1,600 electrical cables were affected, 628 of which were important to plant safety. The fire damaged cables for power, control systems, and instrumentation, which affected reactor safety systems. The fire damaged so many cables that operators could not monitor the plant normally and had to make emergency repairs on the systems needed to shut the reactor down safely.



*Browns Ferry reactor building after the fire*

As a result of the fire at Browns Ferry, fire PRAs were initiated through academic institutions, commercially, and via NRC sponsorship. In fact, the first fire PRA evaluation was incorporated into Appendix XI to WASH-1400, estimating the likelihood of core damage from a fire like that at Browns Ferry. Fire PRA methods, including computer codes to simulate fire progression and damage, were developed. Today, fire PRA under National Fire Protection Association Standard 805, “Performance Based Standard for Fire Protection for Light Water Reactor Electric Generating Plants,” includes the use of analytical tools to evaluate fire safety equipment located within a fire area, as well as post-fire operating procedures.



*Fukushima reactors  
after the tsunami*

Other efforts to understand external events include the research related to seismic and external flood PRAs (internal floods have been part of the internal events PRA process from the early days). The Fukushima Daiichi Nuclear Power Plant suffered major damage in 2011 as the result of a 9.0 magnitude earthquake and consequential tsunami. Following the earthquake, the plant followed emergency procedures, and emergency power was available to cool the reactor cores, which were operating at the time of the earthquake. It was not until the subsequent tsunami hit that emergency alternating current power and vital reactor systems began to fail. The unusually large tsunami led to the eventual core melts in three of the operating reactors. The NRC analyzed events like these, which were caused by a seismic and flooding event, in NUREG-1150, “Severe Accident Risks: An Assessment for Five U.S. Nuclear Power Plants,” issued December 1990.



*Fort Calhoun flooding  
event*

External flooding events have also threatened nuclear power plants in the United States. One of the most notable incidents occurred in 2011 at the Fort Calhoun Station, sited along the Missouri river. These cases highlight the need to understand the risk associated with external flooding and nuclear power plants.

## 8. Conclusion

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### *Probabilistic Risk Assessment Today and in the Future*

The data recorded for over half a century of operating nuclear power plants have increased the use and accuracy of PRA. NUREG-1150 followed the efforts of WASH-1400 by using over 15 years of new data from research and nuclear power plant operation. The results were similar to those in WASH-1400, but they showed that plants were safer than found in the original WASH-1400 analysis.

The NRC issued a policy statement (60 FR 42622, August 16, 1995) that supported risk-informed initiatives by stating the following:

*The use of PRA technology should be increased in all regulatory matters to the extent supported by the state of the art in PRA methods and data, and in a manner that complements the NRC's deterministic approach and supports the NRC's traditional defense-in-depth philosophy.*

In 1998, the NRC published Regulatory Guide 1.174, “An Approach for Using Probabilistic Risk Assessment in Risk-Informed Decisions on Plant-Specific Changes to the Licensing Basis.” In 2004, the NRC published Regulatory Guide 1.200, “An Approach for Determining the Technical Adequacy of Probabilistic Risk Assessment Results for Risk-Informed Activities.” Both of these regulatory guides were crucial for the adoption of PRA seen in current regulations.<sup>10</sup>

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<sup>10</sup> For more information on current PRA initiatives and recent history, see “Probabilistic Risk Assessment and Regulatory Decisionmaking: Some Frequently Asked Questions,” issued March 2016 (ADAMS Accession No. ML16061A559) and NRC Web page “History of the NRC’s Risk-Informed Regulatory Programs.”

The NRC also proposed Recommendation 1 in NUREG-2150, “A Proposed Risk Management Regulatory Framework,” issued April 2012, which would formally adopt a risk-managed regulatory framework; however, the NRC has taken no policy action to implement this recommendation. Dr. Budnitz noted, “There is a lot still in front of us [regarding PRA] and we have the methods, we have the knowledge and we have the people inside the agency.”

Some areas related to nuclear power plant safety (such as high-level waste) have seen heavy use of risk assessment since the 1970s, whereas other areas are still evolving. The transition to a risk-informed regulatory framework is expected to be incremental. Many of the present regulations are based on deterministic and prescriptive requirements that cannot be quickly replaced. Therefore, the current requirements will have to be maintained while risk-informed or performance-based regulations, or both, are being developed and implemented. Although the traditional deterministic approach to regulation has succeeded in ensuring no undue risk to public health and safety in the use of nuclear materials, opportunities for improvement exist.

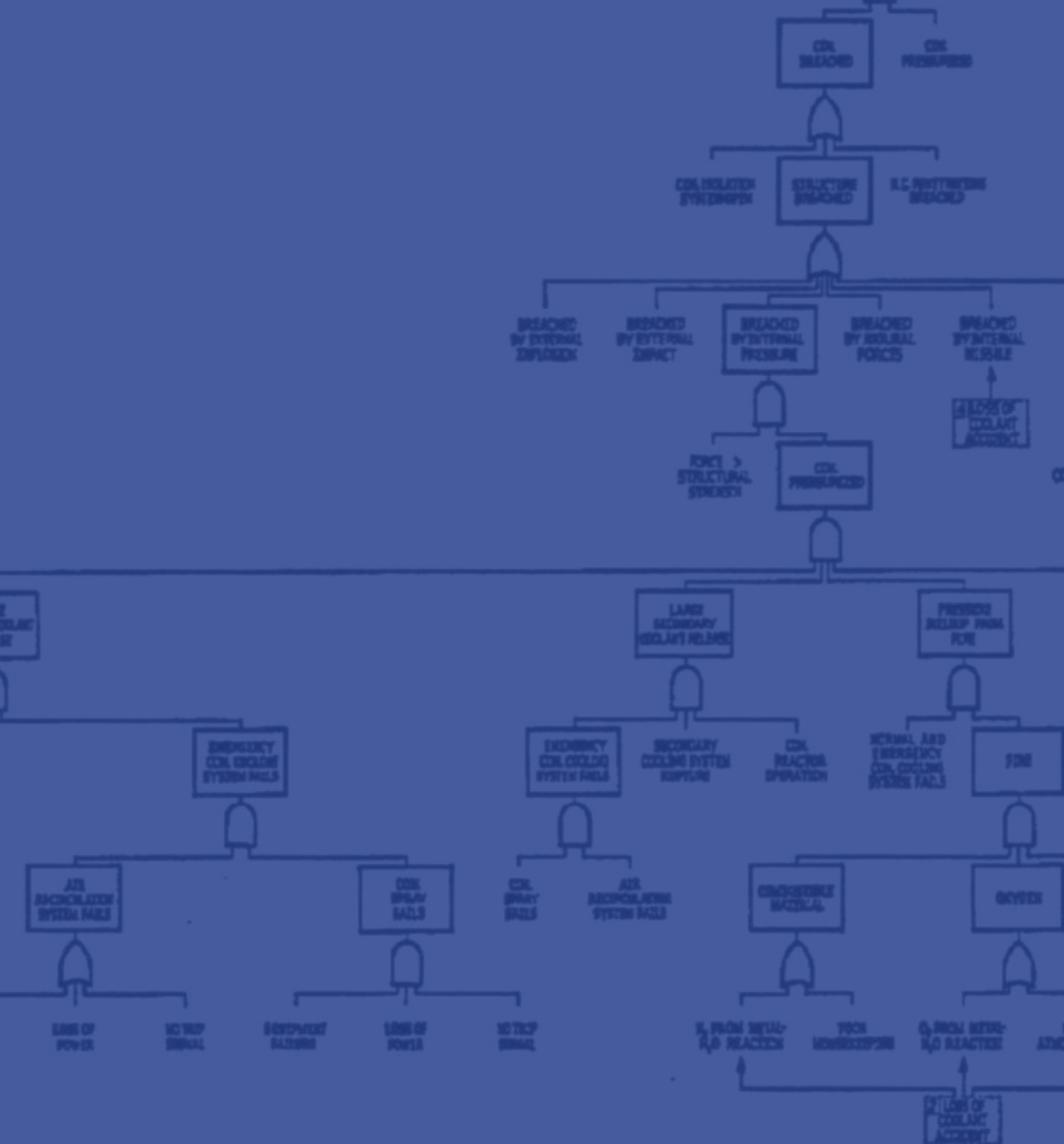
### *Final Remarks*

Since WASH-1400, PRA has evolved into a sophisticated tool used in policy and regulation for nuclear power plants. Many other government and industry studies have contributed to a better understanding of the risks associated with nuclear power plants. Current efforts to create seismic, fire, flooding, and human reliability risk models can be traced back to WASH-1400 and other early attempts at calculating risks. PRA use in the current era helps create an environment of safe nuclear power plants.





<p><b>NRC FORM 335</b> (12-2010) NRCMD 3.7</p> <p style="text-align: center;"><b>U.S. NUCLEAR REGULATORY COMMISSION</b></p> <p style="text-align: center;"><b>BIBLIOGRAPHIC DATA SHEET</b> <i>(See instructions on the reverse)</i></p>	<p><b>1. REPORT NUMBER</b> (Assigned by NRC, Add Vol., Supp., Rev., and Addendum Numbers, if any.) NUREG/KM-0010</p>										
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<p><b>11. ABSTRACT (200 words or less)</b> The history of probabilistic risk assessment in the nuclear industry can be traced back to 1940's even before civilian power reactors. WASH-1400 represented a watershed event for the development and use of risk assessment in the nuclear industry. The events documented in this booklet encapsulate the movements surrounding the development of WASH-1400, how WASH-1400 became a proof of concept for the application of risk assessment, and how risk assessment has influenced nuclear power plant safety regulation today.</p>											
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