To Understand Fukushima We Must Remember Our Past:

The History of Probabilistic Risk Assessment

of

Severe Reactor Accidents

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Thank you for your kind invitation to this 2011 Sociedad Nuclear Mexicana y LAS/ANS Symposium on Nuclear Energy: Key Factors and Challenges as we continue our tradition of participation. I am delighted that good cooperation has been achieved between your Sociedad Nuclear Mexicana y LAS/ANS -- resulting in the joint Los Cabos 2011, the LAS/ANS Annual Meeting as well as the 22nd Annual Symposium of the SNM. I express my sincerest appreciation to the SNM -- both as the host organization for LAS/ANS and as the SNM conference organizer.

Your hospitality has been superb and very welcoming, in your beautiful country. It has been a long time, too long since I was last in Mexico, almost exactly 30 years ago in 1981 on a family vacation. Let me especially thank the LAS/ANS Chairman, Odilon Antonio Marcuzzo Do Canto, and the President of the MNS, Cecilia Martin del Campo Marquez for all of your help.

I also recognize our long-term Latin American contact, Jorge Spitalnik, LAS Treasurer; Juan-Luis Francois, President, Pacific Nuclear Council, and Gustavo Alonso, Immediate Past Chair, International Nuclear Societies Council.

Today I will be sharing my thoughts with you about the future of nuclear energy. Though many tie our nuclear future to the earthquake and tsunami tragedy in Japan, I believe it is premature to establish firm conclusions from those events. It is not my role to tell you today what happened at Fukushima. The ANS Café' provides reports and commentary on the accident and the events that have followed. ANS will ultimately record, archive and disseminate the authoritative analyses of the impacts of the Japan Earthquake and Tsunami Event on the Fukushima nuclear power plants. We are grateful to the Japanese for sharing information which we print in *Nuclear News,* and we hope to continue to work with them in drawing such lessons as we can from this event. The ANS stands ready to support the Atomic Energy Society of Japan (AESJ) and the Japan Atomic Industrial Forum. ANS members have contributed to care and recovery efforts in the region and contributions from other organizations have been forwarded through ANS.

ANS, as part of our mission, joins other nuclear industry professionals in a philosophy of learning, teaching, defense-in-depth, excellence in designs, standards, and conduct of operations. And those operators follow emergency preparedness planning.

Many believe that our nuclear future must be redirected in light of the earthquake and tsunami tragedy in Japan. While we will learn much from this event, I have not diminshed my belief that nuclear power must remain a key component of any rational energy policy.

HISTORY OF PROBABILISTIC RISK ASSESSMENTS OF SEVERE REACTOR ACCIDENTS

A brief historic view of the use of probabilistic risk assessment for the study of severe accidents will be the focus of my address today. The U.S. documents regarding severe accidents with which I am most familiar are WASH-740, WASH-1400, and NUREGs-1150, 5869 and 5856. These studies represent a progression of our understanding and our ability to model actual plants, with the incorporation of actual experience. Among other contributions, they tell us that core damage will occur in hours should it be impossible to provide cooling for the fuel in a nuclear power plant. The industry was clear about this all along, so nobody can claim that we were not aware of this basic fact. We started writing probabilistic risk assessments and severe accident analyses in the early years of nuclear power. In any nuclear power system it is a stable absolute—that heat must be removed both during operation and after shutdown. It is as simple as that.

I want all of us again to become familiar with these severe nuclear accident documents, to recall the results of these analyses, especially in light of the current discussions with regard to the future of nuclear power. So let us begin. Please bear with me as I trace the sometimes confusing acronyms of our industry.

WASH-1400

WASH-1400 "The Reactor Safety Study" (now updated and replaced by NUREG-1150) is a 1975 document that replaced the 1957 "Brookhaven Report," WASH-740. WASH-740 studied the possible consequences of a hypothetical major accident on Long Island New York reactor ***without any containment***—that is, a full-core melt-down followed by an energetic dispersal giving no credit for any containment building whatever its design. WASH-740's worst case scenario assumed that 100% of the core went airborne and drifted over Manhattan. As you can imagine, the hypothetical consequences were substantial! WASH-740 established the standard from which the reactor designer had to scale down by showing quantitative advantages relative to this reference worst-case. Starting from a worst-case analysis that was not even realistic is not a good way to convince people that a system is safe. Clearly, WASH-740 needed updating.

The WASH-1400 study, released in 1975, was nominally directed by Professor Norman Rasmussen of MIT who did high-level thinking. This study was actually written by AEC/NRC staff under the direction of Saul Levine. Rasmussen was the driver, and this is widely recognized as his magnum opus. The WASH-1400 study introduced probability into the analysis of reactor accidents – Probability Risk Assessment (PRA).

Many experts in reactor analysis were involved at one point or another in preparing and negotiating the probabilities used in the study. It took Rasmussen several years to persuade the broader nuclear community and regulatory experts that WASH-1400 with its new PRA concept was a legitimate approach.

What does WASH-1400 tell us today? When it was released, the NRC Commissioners decided it would not be prudent to use this new PRA as a licensing basis until it could be tested against actual designs (hence NUREG 1150 that followed 15 year later). There are dramatic numbers in this report. Yes, some of their "end of spectrum" numbers were originally WAGs. Take a look at Figure 5-3 from the report, which plots the "probability per reactor year events" versus "early fatalities." A worst-case reactor accident, resulting in fatalities,initiated by a worst-case earthquake, would only occur about once in a billion reactor years of operation. The report puts this risk into context by comparison: "Based both on worldwide experience and estimates such as described above, extrapolation indicates that up to 100,000 fatalities might occur for a severe earthquake occurring in the U.S." If one nuclear power plant was put into the same geographic location it would add 1,000 to 2,500 additional fatalities. A one-percent increase. The earth is a dangerous place to live.

As nuclear professionals we NEED to acknowledge that WASH-1400 exists as a worst case scenario, while pointing out that models and assumptions change as we get new information. Some examples:

- The postulated melt down with a steam explosion rupturing both the reactor vessel and containment and the ejection of 50% of the core did not occur at SL-1 or Three Mile Island or Chernobyl.
- It's the spent fuel pools in the U.S. nuclear fleet that have the largest radioactive inventory, not the reactor cores. WASH 1400 assumed reprocessing that would keep spent fuel inventory low, not the high density racking that we have today.
- The estimate that 1,000 reactor-related early fatalities after a large earthquake is wrong.

In hindsight, the contrast between WASH-1400's dire predictions and our history of relatively benign consequences of actual serious reactor accidents tend to raise the suspicion that there might have been a certain amount of "fear mongering" involved— to keep R&D money being allocated by NRC and AEC/DOE flowing to the nuclear reactor safety research sector "to make nuclear power safer." With more realistic thinking, striving to learn and do better, our nuclear professionals countered WASH-1400 with NUREG-1150.

NUREG-1150

NUREG-1150 "Severe Accident Risks: An Assessment for Five U.S. Nuclear Power Plants," was issued in 1990. It was undertaken to reexamine the two reactors considered in WASH-1400, using improved methods of analysis and expanding the analysis to include three more specific plant designs. It improved the treatment of uncertainties, a process that is integral to the job of assessing the probabilities of risks from severe accidents. NUREG-1150 evaluates two U.S. BWRs and three U.S. PWRs which operated sufficiently long to provide a valid data base. Table 1, provides a summary of the five plants studied:

Table 1: Five U.S. Nuclear Power Plants Evaluated in NUREG-1150

Name	Type	Containment	Vendor	Constructor	Operation
Surry (2 Units)	PWR (3 loops) 788MWe	Dry-sub atmospheric	Westinghouse	Stone & Webster	1972-present
Peach Bottom	BWR-4 1065MWe	Mark I	GE	Bechtel Corp.	1974-present
Sequoyah (2 units)	PWR (4 loops) 1148 MWe	Ice condenser containment	Westinghouse	TVA	1981-present
Grand Gulf	BWR-6 1,250MWe	Mark III	GE	Bechtel	1985-present
Zion (2 units)	PWR (4 loops) 1,100MWe	Prestressed concrete, steel lined dry containment	Westinghouse	Sargent & Lundy	1973-1998

The NRC had many objectives in writing NUREG-1150:

- Provide an assessment of possible severe accidents in water cooled reactors.
- Provide a snapshot of nuclear risks affecting the public, based on plant designs (BWR vs. PWR), containments (dry vs. suppression pool), operational characteristics and the plants' proximity to cities.
- Identify plant-specific risk vulnerabilities for each plant. We call that "risk-informed analysis."
- Summarize the perspectives gained in performing these risk analyses so that other nuclear plant risk studies could be completed.

In short, NUREG-1150 validated Probabilistic Risk Assessment (PRA) as another tool to help us, the nuclear technologists, understand and present the probability of a severe accident and estimate its consequences. NUREG-1150 is a very important document for our nuclear power technology.

Note the content between PWR and BWR in this NRC study is markedly different since they were assigned to different national laboratories. Table two provides a comparison of the key attributes of each plant.

Table 2: NUREG-1150 Key Plant Attributes

Attribute	Surry (Ch3)	Peach Bottom (Ch4)	Sequoyah (Ch5)	Grand Gulf (Ch6)	Zion (Ch7)
Plant type	PWR (3 loop)	BWR 4	PWR (4 loop)	BWR-6	PWR (4 loop)
Coolant injection systems	3	7	3	9	3
Heat removal	2	3	2	3	2

systems					
Key Support Systems	Batteries 2 Diesel (self-cooled) Service water is gravity-fed	Batteries 4 Diesels Service water shared by 2 units	Batteries 4 Diesels Component cooling water Service water system	Batteries 2 Diesel Suppression pool Standby service water	Batteries 5 diesels
Battery time	2 hrs	10 – 12 hrs	2 hrs	12 hrs	(not given)

Chapters 3 through 7 provide a clear illustration of the features of each of the plants analyzed, and how the frequency of core damage is estimated. My read, my summary, is provided in Table 3. It shows that plant-specific differences in the designs DO make a difference in the calculated mean frequency core damage. As you re-read Chapters 3 through 7, you will draw your own conclusions.

Table 3: NUREG-1150 U.S. Nuclear Power Plants Risks Comparison

Attribute	Surry	Peach Bottom	Sequoyah	Grand Gulf	Zion
Core damage frequency/reactor yr	3 E-5	3 E-6	4 E-5	3 E-6	2 E-4
Possible internal accident sequences	5	4	5	2	6
Range of time to core damage	5 min to 8 hours	15 min to 13 hours	Not provided	20 min to 12 hours	Not provided
Maximum early fatalities	1,000	3	3,000	30	10,000

We, as publicly-recognized technologists, need to be meticulous when comparing numbers for the five different technologies, all with different types of containment. When you re-read these chapters of NUREG-1150 consider the distribution around the core damage frequency. Today - and tomorrow - with the developing data from Fukushima, we need to recognize the input and impact from new external events.

The NRC stated that NUREG-1150 should be used as follows:

- Developing guidance for individual plants from internally or externally initiated events;
- Developing accident management strategies;
- Developing plans for coping with emergencies and their consequences;
- Analyzing the need for improving containment performance under severe accident conditions, and in devising appropriate ways to do it;
- Analyzing alternative strategies for implementing safety goals;
- Characterizing the importance of a plant's operational features and areas potentially requiring improvement;

- Prioritizing research projects;
- Prioritizing generic issues.

The media have wrongly referenced this document at times, ignoring the NRC's guidance—and yes, our resource documents have been used against us again. The take-away for us all: NUREG-1150 is a <u>resource</u> document!

NUREG-5869 and 5856

NUREG-1150, published in 1990, was followed two years later by NUREG-5856 and NUREG-5869. These two NUREGs provide further insight into strategies for dealing with severe accidents in PWRs and BWRs. They also initiated the Individual Plant Examination (IPE) and Individual Plant Examination for External Events (IPEEE) programs. As I stated in the beginning of this address, these documents demonstrate that our mission as nuclear professionals is to continue digesting and implementing the lessons learned to improve the discipline of nuclear energy.

I suggest that each of you add to your list of 'must-read documents' the NUREG-5869 "Identification and Assessment of BWR In-vessel Severe Accident Mitigation Strategies." It was published in 1992, a technical effort supported by Oak Ridge National Laboratory. Mexico has one BWR, and this document tells BWR owners and operators how to operate better.

For PWRs, I suggest you add to your reading list, NUREG-5856 "Identification and Assessment of PWR In-vessel Severe Accident Mitigation Strategies" which was also published in 1992. It was technically supported by Pacific Northwest Laboratory (PNNL) with some support from Brookhaven National Laboratory (BNL).

We can re-learn from both of these BWR and PWR documents a couple of lessons that are generic for all LWRs:

> ". . . almost all potentially beneficial strategies require electrical power. Thus, strategies to restore either offsite AC power or emergency AC power are of the highest urgency"

and

> "A utility with multiple nuclear units could purchase a single, centrally located skid- or truck-mounted diesel or gas turbine generator to provide last-resort AC power backup to all of its plants. This generator should be able to reach any plant in the system within a couple of hours. Single-unit utilities might join with neighboring nuclear utilities to cooperatively purchase such emergency generators."

These conclusions on the need for electrical power should be noted as being reinforced by the most evident lesson from the Fukushima event.

The bottom line from this brief History of Probabilistic Risk Assessments of Severe Reactor Accidents is that this sequence of analyses shows a steady progression of increased understanding and increased realism, leading to ever higher confidence in the safety of nuclear installations. We can expect the next level of understanding to arise when the events at

Fukushima are fully understood.

Courage going forward

My hope is that all of us can recognize how these historical, severe-accident studies relate to our current professional responsibilities. We have identified the events originating outside the nuclear island that have the potential to cause reactors to fail in various ways, and we have identified mitigating strategies for removing the decay heat when reactors are shut down.

Should nuclear power continue on an earth where severe accidents can happen? Yes.

Should nuclear power continue to thrive as we humans struggle against natural accidents? Yes.

Can humankind conscript ourselves to win against earth and wind and sea? No. If you want to understand why we cannot always win, please read John McPhee's book "Control of Nature" published in 1989.

In just three chapters, McPhee takes the reader deep into the contested, unstable territories of people trying to control the biggest river in North America, island lava flows, and a disintegrating mountain range. Nature is complex and awesome. Our Earth still challenges us with instabilities beyond our control. We all suffer from a fatal illness called "life." None of us will survive from being alive.

Courage is what allowed humans to harness atomic energy, and courage will carry us forward after Fukushima. Yes, we live on a very unsafe place called Earth. Realize that each year Earth suffers at least one earthquake with magnitude greater than 8.0. More than one million earthquakes with levels between 2 and 3 occur each year. And if earthquakes don't scare you, how about tornadoes? So far this year, 481 lives have been lost to tornadoes in the U.S. alone! More than 20,000 people died as a result of the March 11 tsunami, none of them from radiation.

Earth is a dangerous place. Nuclear power's safety record is much better than Earth's overall safety record. Nuclear power continues to be the safest large scale energy source.

The major lesson we learn from the Fukushima event is the power of water: a wall of sea water transformed a coast line into a multi-billion dollar clean-up. The nuclear plant buildings suffered damage, but the hardened structures stood while enormous swaths of infrastructure, industries and homes were swept away. Many, many suffered much. But Japanese society will recover.

Newer nuclear plants and advanced designs for nuclear plants now under construction already incorporate significant advances in long-term cooling, and we should thoughtfully apply our engineering awareness and prowess. Like all professionals, we have improved our craft. We are going to keep our current fleet of power plants running because they are the world's safest major energy source.

Fukushima will provide a vast amount of information to our profession after more detailed examination of the cores and reactor components, and of the conditions in the facility following the event. This is an expensive way to learn how fuel and components perform under severe accident situations, but it promises to be tremendously valuable. We must work to better our understanding of ways to improve even more the safety of our already-very-safe reactor plants.

As for the future prospects for nuclear power, there is good news and bad news. The bad news you have read. The good news is that during this external event, when earth released energy in the form of an earthquake, followed by a tsunami that subjected the Fukushima site to massive physical damage, the human-designed-and-built nuclear infrastructure limited the release of all but the most volatile fission products. This should give renewed confidence in the inherent dependability of nuclear plants, NOT the opposite. The next generation of nuclear power plants will be even more stable—and we do not need to stop licensing in the U.S. or construction elsewhere to "go figure it out."

All societies need abundant, stable energy. Today we must step up and start building these new plants, even as we study the unfortunate Fukushima incident to learn how to institute low-cost, more secure back-up systems. The nuclear part of the plant has killed not one. Yes, two nuclear plant workers were swept by the tsunami since they did not stay in the buildings. Two others have died of a fall and a heart attack, but I wonder whether the oil refinery down the coast had similar industrial safety issues. And, finally there has been and will continue to be radiation exposure from the damaged fuel; however, we need to be careful of claims that this will cause a measurable amount of fatalities in the future. How do we compare drowning in 4 minutes to a slightly increased probability of dying of cancer in 40 years?

On a more philosophical note, do we need to rebuild the entire public infrastructure and each home in California and Mexico to withstand a magnitude 9.0 earthquake, because they are geographically in the world's greatest earthquake zone—the circum-Pacific seismic belt? Better known as the "Ring of Fire," this belt forms the rim of the Pacific Ocean, where about 81 percent of the world's largest earthquakes occur—the Fukushima quake being one of them. Does Japan have to rule out the return of over a million people to cities and towns in the flood plain?

And what are we doing about the virtual certainty that a large meteor will someday strike our earth? Can't happen? Well, it did happen here, about 65 million years ago, when the Yucatan Peninsula was struck by an asteroid estimated to be at least 10 km (6 miles) in diameter. It created a crater more than 180 km (110 mi) wide—one of the largest confirmed impact structures on earth—and it led to the extinction of the dinosaurs.

Let us recognize our challenges. Let's use our knowledge, and share it, and continue to implement our improvements in nuclear science and technology. Let us continue to build new nuclear power plants.

How do we come to closure on Fukushima? We absorb the blow, learn its lessons, and move on. This adversity will make us better, and our plants stronger. From the severe and heart-rending lessons of Fukushima will come the recognition and a deeper respect for heat from the decaying nuclei of radioactive atoms.

Would all of you please stand.

We stand in respect for the loss of more than 24,000 people in Japan due to an unsafe and unstable earth.

We stand to commit to learn from Fukushima.

Please applaud yourselves for your efforts and your future commitments to stand together as we improve nuclear technology.

Acknowledgments: The inspiration for this address came during my 2005 reading of John McPhee's 1989 book titled "Control of Nature" (I read the book the month before the hurricanes struck the Gulf coast of the U.S.). McPhee's book predicted the flooding of New Orleans that we all witnessed on TV.

The following individuals improved this initial inspiration with information and comments: Sama Bilbao, David Rossin, W.H. Hannum, and George Stanford. Thank you.