# THERMAL HYDRAULICS DIVISION NEWSLETTER

## Spring 2011

**Message from the Chair**

Dear Colleagues,

On behalf of the THD Executive Committee, it is my great pleasure to send this message as Division Chair in this foreword to the Newsletter.

First of all, let me start with our deepest sympathy for all those affected by the tragic chain of events, especially the nuclear accident at Fukushima Daiichi Nuclear Power Plant, following the devastating earthquake and tsunami that struck Tohoku region of Japan on March 11, 2011.

As of today, in the No. 1 to No. 3 BWR units of the Fukushima Daiichi NPP, it is still necessary to inject water into the reactor pressure vessel to keep the reactors cool. The amount of water injection needed is the make up for the evaporation plus leakage from the RPV. Far more than 100,000 tons of highly contaminated water is estimated to have leaked from the RPV/primary boundary and out of the primary containment vessel (PCV) of type Mark-I, and is now in the reactor and turbine buildings. The contaminated water, also from the spent fuel pools, is flooding a large portion of the basement space. This is a consequence of the failure in removing the decay heat generated in all three units since the gigantic tsunami has washed away all the engineered safety systems in place and caused station blackout (SBO) around 3:40 PM, one hour after the M9 quake. SBO has disabled every decay heat removal capability except for the Isolation Condensers (IC) installed in Unit 1. However, the IC did not work long enough for some erratic reasons. With the PCV isolated and without any decay heat removal and transport capabilities to outside of the PCV (Loss of Ultimate Heat Sink), the cores of the three units started to heat up and melt and eventually part of the cores melt down to the bottom of the RPV. The timing of the core melt depended on the termination of IC for Unit 1 and of Reactor Core Isolation Cooling for Units 2 and 3. In other words, the timing was dictated by the amount of water available inside the PCV. The core melt has been a rapid process and happened within a few days. The venting and following (borated) water injection were made too late and hydrogen explosions followed the ventilation. At that time, I considered the PCV flooding was the only way to save the RPVs, but no action was taken possibly due to no electricity and/or mobile generators/pumps available in time. All the physical sequences lie in the realm of thermal hydraulics and our expertise in the area. Our contributions are strongly required to identify and clarify the physics involved.

The nuclear industry is faced with challenges due to the Fukushima Daiichi accident. Nuclear safety must be enhanced in a balanced way with other challenges, such as radioactive waste management, economics, and non-proliferation. We recognize, nevertheless, the heightened importance of plant safety with lessons learned from the accident, where thermal hydraulics research and development play a significant role in supporting safe operation of nuclear plants and fostering safety culture. In view of the global nature of these nuclear issues, it is imperative that our thermal hydraulics division plays an important role to enhance exchange of ideas and critical information and encourage cross-fertilization of research and development efforts among not only in the USA but all countries that peacefully utilize nuclear energy.

Having discussed the Fukushima reactor accident, I resume the regular newsletter foreword on the division vitality. As always, one of the key indicators is the membership trend. The number of members had stayed almost constant in 2008 and 2009, but increased considerably in 2010 (From about 9.3% of the total ANS membership to 9.8%. Please see the Membership Committee Report in this newsletter for details). The next few years may, however, place us in a situation different from the one anticipated before, a less optimistic nuclear renaissance. If so, we need to further our efforts to recruit young professionals, domestic and international, who take part in and energize more of our Division activities.

Of importance is an extent to which the Division has attained its internationalization. Since I have joined the Division governance about a decade ago, I have witnessed the THD history made by the past Chairs and all the members of Program and Executive Committees. I am totally in agreement with the immediate past Chair Karen Vierow that the Division has strived to remove international borders within the nuclear technical community. As a consequence, the Division has become real international and borderless. Its mode of operation is globally oriented. As one of the international

members, I am proud of having been a constituent of this steady stream of Executive Committee members and Officers of the Division from abroad who are elected to their posts by the Division members.

Our thermal hydraulics division has played an important role in providing forums, such as our international topical meetings, as a global communication channel. It is no exaggeration to say that the recent success reported in the Topicals, held in the last decade including NURETH and NUTHOS, all relied on the Division's international credibility. To that extent the Division has become and is international.

Other important indicators should include the number of sessions organized in the ANS Annual and Winter Meetings and the number of participants. For instance, please take a look at the Official Program for the 2011 ANS Annual Meeting and join us in Hollywood this June for our nine technical sessions from Monday to Thursday and a Special Panel Session "The Accident at Fukushima Daiichi– Preliminary Investigations," 4-6 PM Tuesday, June 28. You will find the details of these nine sessions under Program Committee Report in this newsletter.

Our future depends totally on student and young members. Therefore, the Division must be attractive to them. In this respect, the Division puts a high priority on providing financial support for student conferences, meeting travel and scholarships. We are working with the Young Members Group, serving as their Technical Division sponsor so that they may host such technical sessions as Research Competition at the national meetings. Without young members' positive participation, we cannot make the Division attractive nor draw Division's bright future.

It will require extended efforts to make the Division useful and attractive to the members. The primary mission of the Thermal Hydraulics Division is to establish, stimulate, and maintain quality technical and professional approaches in all areas of Nuclear Thermal Hydraulics (Please visit our homepage at http://thd.ans.org/). The Division should always be informative and active, trying to keep the members abreast of new, innovative and sound information from research and development programs all over the world. Our current efforts, in addition to those I have mentioned above, include:

- Collaboration with other divisions
  This effort includes co-sponsoring technical sessions.
- Professional development programs
  The Division is considering offering tutorial sessions at national meetings on specific topics.
- Position statement
  Although it is not officially required by ANS, the Division is considering submitting a position statement.
- International Conferences
  The Division co-sponsors NURETH-14 in Toronto, September 25-29, 2011: http://nureth14.org/. Also we plan to co-sponsor NUTHOS-9 in Taiwan, September 2012 and NURETH-15 in Pisa, Italy, May 2013.

The EC/PC members and officers consist of volunteers. Here I want to express my sincere thanks to all of them. In particular, my special thanks go to our Division officers, Vice Chair/Chair-elect Brian Woods, Secretary Xiaodong Sun, Treasurer David Aumiller, and our Webmaster DuWayne Schubring, for their dedicated work on our Division activities. Especially, since the Fukushima Daiichi accident, I would like to emphasize that without their help in keeping the high profile of the Division, I would not be qualified to write this message while I have been deeply involved in the many activities related to accident investigation and answering media questions in Japan as well as from other countries.

Thank you for your continued support to the ANS Thermal Hydraulic Division. Please feel welcome to contact me and let me and the incoming Chair, Brian Woods know how we can improve Division's services. Looking forward to seeing you soon in Hollywood, Florida!

Hisashi Ninokata, Professor, Tokyo Institute of Technology
2010-2011 Division Chair
ANS Thermal Hydraulics Division
hninokat@nr.titech.ac.jp

## Honors and Awards Committee Report

The winner of the 2010 ANS THD Technical Achievement Award was Professor Per F. Peterson, Chair of the Department of Nuclear Engineering at the University of California, Berkeley. Professor Peterson received this award for his exceptional contributions to the understanding of thermal hydraulics phenomena of significance to advanced nuclear reactors and for his impact on the thermal hydraulics community as a researcher, educator, and leader. He was recognized at both the ANS Honors and Awards ceremony and a special technical session during the 2010 ANS Winter meeting in Las Vegas, NV. During the THD Technical Achievement Award special session, Prof. Peterson delivered a lecture entitled, "Thermal Hydraulics for the Next Generation of Nuclear Reactors." (Pictured above: P. Peterson (left) and H. Ninokata)

During this event, the ANS THD also recognized the 2010 THD Best Paper Award recipients, Elia Merzari and Hisashi Ninokata for their paper, "Proper Orthogonal Decomposition of the Flow in a Rod-Bundle." This paper was published in the proceedings of the 13th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-13) that was held in October 2009 in Kanazawa, Japan. (Pictured above from left to right: H. Ninokata, E. Merzari, K. Muftuoglu, and M. Podowski)

The Technical Achievement Award is the highest award of the THD, and we ask for nominations for the 2011 selection process that will be overseen by the 2011-2012 chair, Professor Shripad Revenkar. The deadline of the submission is July 1, 2011. Details related to this award, including the nomination form can be found at http://thd.ans.org/Awards/Awards.htm.

**Joy L. Rempe**, Idaho National Laboratory
2010-2011 Honors and Award Committee Chair
ANS Thermal Hydraulics Division
Joy.Rempe@inl.gov

## Treasurer's Report

**(a). 2010 Division Financial Report**
**2010 Income**

For 2010, the Division's income of $22,779 included the 2009 carry forward ($19,001), our 2010 member allocation ($2,068) and income from National Meetings ($1,710).

**2010 Expenses**

The Division's expenses included the following:

- $2,000, donation to the ANS student conference at the University of Michigan in April 2010
- $500, donation to the ANS for student travel support to the 2010 ANS Annual Meeting and Winter Meeting
- $500, donation to the ANS for Scholarship/NEED program
- $1,789 in Award-related expenses as follows:
  - THD Technical Achievement Award for 2010 at $1,000
  - Best Paper Award at $500
  - Total for Outgoing chair, Best Paper and Technical Achievement Award plaques of $289
- $23 postage

The balance of the THD general funding account at the close of 2010 was **$17,967.**

**(b). 2011 Division Budget**
The Executive Committee approved the following expenses at the November 2010 meeting:

- $1,800 for awards and plaques (same as in 2010)
- $500 total for student travel support to the 2010 ANS Annual Meeting and Winter Meeting (same as in 2010)
- $2,000 targeted to student support with details to be identified by THD (increase of $1,500 from 2010)
- $500 for Scholarship/NEED program (same as in 2010)

A great deal of discussion took place concerning the funding of the student conference. While the final budget did not include direct funding of the conference, the total amount of student support from the Division is $2,500, which represents a modest decrease of $500 from 2009.

**(c). 2011 Division Financial Report**
**2011 Income**

The year-to-date Division's income of $20,225 includes the 2010 carry forward ($17,967) and our 2010 member allocation ($2,258).

**2011 Expenses (by May 23, 2011)**

The Division's expenses included the following:

- $500, donation to the ANS for student travel support to the 2010 ANS Annual Meeting and Winter Meeting
- $500, donation to the ANS for Scholarship/NEED program

The estimated balance of the THD general funding account as of May 23, 2011 is **$19,225.**

David Aumiller
2010-2011 Treasurer
ANS Thermal Hydraulics Division
David.Aumiller.Contractor@unnpp.gov

## Program Committee Report

The strong THD presence at the national meetings continues. The interest and participation to the sessions organized by our division reached a new high: we have received the record number of summaries and a record number of sessions put together. In fact, we are running parallel sessions for Monday and Wednesday afternoons at the conference at the 2011 Annual Meeting in Hollywood, Florida. Thanks to the support of the authors, session organizers, reviewers, and other contributing members, the program committee has put together another strong arrangement of sessions for this Annual Meeting.

At the 2011 Annual Meeting, THD is organizing total of 9 sessions: 8 contributed paper and 1 invited paper sessions. This meeting also marks one of the highest numbers of summaries for THD sessions. We have received a total of 62 summaries and 57 summaries will be presented at the meeting. Again, let me take the opportunity to thank for all the efforts of the session organizers and the reviewers. The sessions, in chronological order, are:

- Next Generation Safety Analysis Code, [Mon. p.m.]
- Thermal Hydraulics of Gas-cooled Reactors—I, [Mon. p.m.]
- General Thermal Hydraulics—I, [Tues. a.m.]
- Computational Thermal Hydraulics—I, [Tues. p.m.]
- Thermal Hydraulics of Gas-cooled Reactors—II, [Wed. a.m.]
- Thermal Hydraulics of Small Modular Reactors, [Wed. p.m.]*
- Experimental and Computational Two-Phase Flow, [Wed. p.m.]*
- General Thermal Hydraulics—II, [Wed. p.m.]

*: These are two split "half" sessions. The second session will follow the first session immediately in the same room.

- Computational Thermal Hydraulics—II, [Thur. a.m.]

THD is co-organizing a Special Panel Session with ESD, NISD, OPD, and RPSD: The Accident at Fukushima Daiichi—Preliminary Investigation on Tuesday. This session will start at 4:00 pm. Prof. Hisashi Ninokata is a panelist representing THD.

For the 2011 Winter Meeting at Washington, DC, the division is planning to organize six sessions. The sessions planned for the Winter Meeting are as follows:

- General Two-Phase Flow
- Experimental Two-Phase Flow
- Computational Thermal Hydraulics
- Thermal Hydraulics Code Verification and Validation
- Thermal Hydraulics: General
- Young Professional Thermal Hydraulics Research Competition

There is still time to submit summaries to this Winter Meeting if you wish. The deadline of the submission has been extended to June 24, 2011.

At the Executive Committee meeting, June 2010 San Diego, CA, THD has approved preparing an embedded topical meeting which will be held during the 2012 Winter Meeting. This will be a peer-reviewed full-length paper topical meeting. The calendar placement with the National Program Committee (NPC) is completed. The actual preparations for the meeting will begin later this year. Based on the recent year numbers, the meeting is expected to attract significant participation. This will also serve our membership and research community as a venue for full-length papers. More details will be announced as they become available by email list and the newsletter.

The THD Program Committee meeting will be held on Sunday June 26, starting at 2:30 p.m. in Room 312, following the NURETH-14 Technical Program Coordination meeting. The meetings are open to everyone interested. We are continuously looking for members to partake in our division activities. This meeting is a good opportunity to learn and observe the PC activities. To find out more on how to get involved, please contact the Division's Program Committee chair.

**Kurshad Muftuoglu**, GE-Hitachi Nuclear Energy
2010-2011 Program Committee Chair
ANS Thermal Hydraulics Division
PCchair@thd-ans.org

## Report from the Conference Selection Committee

The Conference Selection Committee received three proposals for NURETH-15 and one proposal for NUTHOS-9. The NURETH-15 proposals were submitted by Italy, ANS Chicago Section, and ANS Wilmington Section. The Committee selected the Italian proposal based on its strength as well as the requirement that NURETH be held outside of North America every other time. The committee also provided the evaluation comments and suggestions for the two US proposals and advised the two ANS sections to incorporate them in their revised proposals if they choose to resubmit them for consideration for NURETH-16. NURETH-15 will be held in Pisa, Italy, May 12-19, 2013 as an ANS Class II event. The Conference Chair is Prof. Francesco D'Auria of the

University of Pisa (UNIPI) at francesco.dauria@dimnp.unipi.it with support of Technical Program Chair Dr. N. Aksan (formerly of PSI). Prof. D'Auria will also act as the THD liaison for the conference.

The committee also evaluated the sole proposal for NUTHOS-9 submitted by Taiwan and selected it. The conference will be held in Kaohsiung City in September 2012 with exact dates yet to be determined. Dr. Chuen-Horng Tsai, Chairman of the Atomic Energy Council of Taiwan, will chair the conference and Dr. Yin-Bang Ma (Director General of INER) will serve as Technical Program Chair. This conference is an ANS Class IV event. The THD liaison for the conference is Dr. Jason Chao at drjasonchao@yahoo.com.

**Jong H. Kim**, EPRI
Conference Selection Committee Chair
ANS Thermal Hydraulics Division
JKIM@epri.com

## NURETH-14 Report

NURETH-14 is rapidly approaching!

The **14th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-14)** will be held in September 25-30, 2011 in Toronto, Ontario, CANADA. Continuing the tradition of the highly successful series of thirteen conferences, NURETH-14 will bring together an international group of leading industry practitioners and academic researchers engaged in engineering and scientific work focused on nuclear reactor thermal hydraulics. This is the only major conference series devoted solely to the advancement of knowledge in the nuclear reactor thermal hydraulics field. NURETH-14 is held under the co-sponsorship of the Canadian Nuclear Society (CNS) and Thermal Hydraulics Division of American Nuclear Society (ANS), in cooperation with International Atomic Energy Agency (IAEA) and the OECD Nuclear Energy Agency (NEA).

Organization and planning for this conference is well advanced. A total of 588 abstracts were accepted earlier this year from which approximately 450 draft papers have been received and subject to peer review. Acceptance letters and review comments have been returned to authors for paper finalization. This large number of papers indicates the strong interest in this major conference. The arrangement of papers into technical sessions is underway. In addition, a number of plenary sessions, keynote speakers and special topical sessions have been arranged. Of particular topical interest is a special panel session that has been arranged on Lessons Learned from the Fukushima Accident. An international group of panelists from Japan, USA, Europe and Canada will participate in this session. A major push is ongoing to engage more sponsors of the conference and increase the number of exhibitors.

NURETH-14 is a unique opportunity for researchers and practitioners in the field to present results of their work and to discuss challenges and new ideas with attendees. Make your plans now to attend NURETH-14 and enjoy the technical, social and cultural events associated with this important conference! Visit the NURETH-14 website at http://nureth14.org/ to obtain more information, to register and to make your hotel bookings.

**John Luxat,** Professor, McMaster University
General Chair, NURETH-14
luxatj@mcmaster.ca

## Young Professionals Report

We have been working with the Young Members Group for the co-sponsoring of the Young Professionals Thermal Hydraulic Research Competition. This competition focuses on thermal hydraulic research completed by members early in their career. Participants must be less than 36 years old or have less than 5 years of Thermal Hydraulics research or application (YMG membership criteria). Students will be considered, but priority will be given to recent graduates and professionals with limited experience. More information regarding the competition can be found on the THD website: http://thd.ans.org/YPTHRC11.pdf.

**Brian Collins**, Pacific Northwest National Laboratory
**Elia Merzari**, Argonne National Laboratory
Brian.Collins@pnl.gov; emerzari@anl.gov

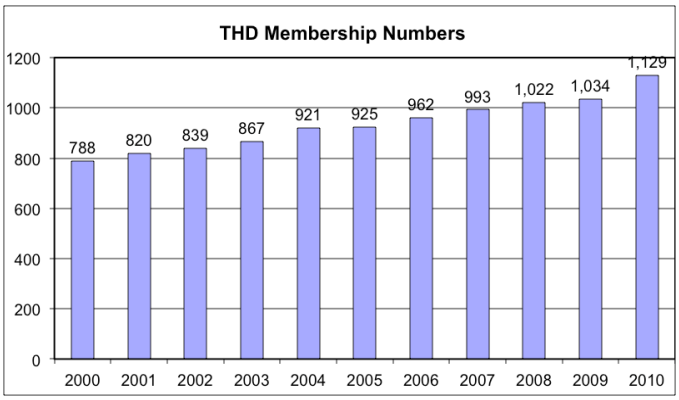
## Web Page Report

The official website of the ANS Thermal Hydraulics Division is located at http://thd.ans.org. The THD committee membership and minutes, conference announcements, newsletters, and awards are all updated as they change throughout each year. THD also maintains a directory of past and present active members at http://thd.ans.org/people.html. This directory was recently updated with contact information from THD governance documents and internet searches. Please check your contact information on this page. If you are not included and believe that you should be (i.e., you are active in THD activities), please provide me with your contact information for inclusion. I welcome any other feedback on the website you would have, either via e-mail or at ANS meetings.

**DuWayne Schubring**, University of Florida
2010-2011 Webmaster
ANS Thermal Hydraulics Division
dlschubring@ufl.edu

## Membership Committee Report

Of the 11,557 ANS members in 2010, 1,129 members (9.8% of the total ANS membership) have selected the THD as one of their professional divisions. As the bar chart below demonstrates, the THD is showing strong growth. In 2010, the Division membership had a 9.2% growth from the previous year. As a reference, membership in the THD peaked in 1993 with 1,184 members. As a consequence of an aging workforce and our industry's recession through the rest of 90s, our membership reached a minimum of 691 in 1999. With strong thermal hydraulic programs planned for the next several years (i.e., NURETH-14 and 15, and NUTHOS-9), we hope our THD membership to grow further.




**Karen Vierow,** Texas A&M University
2010-2011 Membership Committee Chair
ANS Thermal Hydraulics Division
vierow@ne.tamu.edu

## Nominating Committee Report

Current Division Officers and Executive Committee members are listed below.

**Current Year THD Officers (June 2010 – June 2011):**

**Division Chair:** Hisashi Ninokata, *hninokat@nr.titech.ac.jp*
**Vice Chair/Chair-Elect:** Brian Woods, *woodsb@ne.orst.edu*
**Secretary:** Xiaodong Sun, *sun.200@osu.edu*
**Treasurer:** David Aumiller, *david.aumiller@unnpp.gov*

**Executive Committee Members**

| | |
|---|---|
| Hisashi Ninokata (2011) | *hninokat@nr.titech.ac.jp* |
| Brian Woods (2011) | *woodsb@ne.orst.edu* |
| Hee Cheon No (2011) | *hcno@kaist.ac.kr* |
| David Aumiller (2011) | *david.aumiller@unnpp.gov* |
| Randall O. Gauntt (2012) | *rogaunt@sandia.gov* |
| John Luxat (2012) | *luxatj@mcmaster.ca* |
| Stephen Bajorek (2012) | *Stephen.Bajorek@nrc.gov* |
| Cesare Frepoli (2012) | *FrepolC@westinghouse.com* |
| Steven A. Arndt (2013) | *steven.arndt@nrc.gov* |
| Si Young Lee (2013) | *si.lee@srnl.doe.gov* |
| Xiaodong Sun (secretary) | *sun.200@osu.edu* |
| Karen Vierow (ex-officio) | *vierow@ne.tamu.edu* |
| Mikey C. Brady-Raap* | *Michaele.BradyRaap@pnl.gov* |

*Chair of the ANS Professional Divisions Committee, ex-officio member without vote

**Committee Chairs:**

Program Committee – Kurshad Muftuoglu
Honors and Awards Committee – Joy Rempe
Nominating Committee – Karen Vierow
Membership Committee – Karen Vierow

Based on the election earlier this year, the incoming Division Officers for next year and new elected Executive Committee members are listed below.

**Incoming THD Officers (July 2011 – June 2012):**

**Division Chair:** Brian Woods, *woodsb@ne.orst.edu*
**Vice Chair/Chair-Elect:** Xiaodong Sun, *sun.200@osu.edu*
**Secretary:** David Aumiller, *david.aumiller@unnpp.gov*
**Treasurer:** Si Young Lee, *si.lee@srnl.doe.gov*

**Executive Committee Members (3 Years)**

| | |
|---|---|
| Fan-Bill Cheung (2014) | *fxc4@psu.edu* |
| Yassin A. Hassan (2014) | *hassan@ne.tamu.edu* |
| Jong H. Kim (2014) | *JKIM@epri.com* |
| DuWayne L. Schubring (2014) | *dlschubring@ufl.edu* |

The Nominating Committee is responsible for the nomination of THD members to leadership positions on both the Program and Executive Committees. The THD would like to encourage members interested in becoming more involved to contact one of the officers listed above. In particular, the division is usually in need of volunteers for technical meeting session organizers and paper reviewers.

**Karen Vierow,** Texas A&M University
2010-2011 Nominating Committee Chair
ANS Thermal Hydraulics Division
vierow@ne.tamu.edu

## Editor's Note

The following article was written by Professor Shripad Revankar in early May 2011, primarily based on the public information available then. Some efforts were made later to update the information presented in the article.

## Reactor Safety and Fukushima Nuclear Reactor Accidents

*Shripad T. Revankar, Purdue University and POSTECH*

### The Accident

The nuclear reactor accident that occurred on Friday, March 11, 2011 at the Fukushima power plants in Japan is a unique situation where Tohoku-Taiheiyou-Oki earthquake of high Richter scale (9) coupled with tsunami of 14 meter (40 feet) high waves caused sustained loss of both the offsite and onsite power systems. The reactors were shutdown automatically. However the efforts to restore power to emergency equipment were hampered and impeded by damage to the surrounding areas due to the tsunami and earthquake. Loss-of-coolant to the core resulted in severe accidents in 3 units (out of 6). It appears that events that were *beyond the design basis* caused the *station blackout* accident to the Fukushima Daiichi nuclear power station. It should be noted that, in accordance with rules established by the Japanese regulatory authorities, these plants were designed to take the ground accelerations associated with an earthquake of 8.2 on the Richter scale and an associated tsunami (assumed to be 5.7 m high), but obviously not one which had the height/strength of the massive tsunami which actually hit these plants.

The Fukushima power plants are BWR/3 (Unit 1) or BWR/4 (Units 2, 3, and 4) type nuclear reactors (the first ones having both internal jet pumps and steam separators) with Mark–I pressure-suppression containments (Please note that Japanese built Mark-I containment systems are somewhat larger than the GE system. Fukushima Daiichi unit-6 has a Mark-II type containment design). Units 1, 2 and 3 were operating at the time of the earthquake and Units 4, 5 and 6 were shut down for refueling outages at the time of the earthquake.

The fuel assemblies for Unit 4 had recently been offloaded from the reactor core to the spent fuel pool (SFP). The SFPs for Units 5 and 6 appear to be intact. Emergency power is available to provide cooling water flow through the SFPs for Units 5 and 6.

The earthquake caused Units 1, 2 and 3, which were operating at Fukushima, to automatically shutdown where the control rods were automatically inserted rapidly, thus terminating the fission process as these plants were designed to do. The reactors were then put into a safe shut down cooling mode using the plant's isolation condensers (ICs) for Unit 1 and a reactor core isolation cooling system (RCIC) for Units 2 and 3, after the closure of the main steam isolation valve (MSIV) and with a signal of the reactor pressure being high (For Unit 2, a residual heat removal system was also activated). These systems keep the reactor core covered with water and remove the decay heat generated by the radioactive decay of the radioactive fission fragments in the nuclear fuel (e.g., subsequent to a shutdown, the power level of the core drops from full power operation to an initial decay heat power level of about 5 to 3% of full power, and then this power level slowly decays with time after that). This continued until the large tsunami arrived which knocked out any offsite electrical power and disabled the plants' emergency diesel generators (which had been brought on right after the earthquake struck). The ICs and RCIC, powered by the high-pressure steam from the reactor pressure vessels (RPVs) apparently continued to work (DC power is required, however, to keep the logic circuits to control the opening and/or closure of MO- and AO-valves in these systems). But this mode of cooling was terminated about eight hours later for Unit 1, 3 days later for Unit 2, and 2.5 days later for Unit 3 when the batteries presumably became depleted (The battery life was 8 hours; but with careful battery management, the life was extended remarkably for Units 2 and 3).

Subsequently, the water level in the reactor cores began to drop and once the upper part of the fuel was no longer submerged, it began to heat up due to the decay heat. When the zircalloy cladding surrounding the fuel rod pellets gets hot enough, an exothermic zirconium/steam oxidation reaction occurs ($Zr + 2H_2O = ZrO_2 + 2H_2$), which generates a substantial amount of hydrogen gas, and this gas and the steam generated due to boiling of the residual water in the core build up the pressure in the RPV. The pressure in the RPV was subsequently reduced, presumably by discharging these gases into the water pool of the torodial shaped wet well of the Mark-I (e.g., Unit-1) pressure suppression containment (Figure 1). Hydrogen, being a non-condensable gas, does not remain in the pressure suppression pool, but collects in the upper wet well and dry well regions of the Mark-I containment (which was initially inerted with nitrogen gas).

In order to prevent an over-pressurization of the containment structure, these gases were vented by the reactor operators (some of these gases apparently accumulated in the reactor building). When hydrogen gas is vented, a combustible mixture may form. As a consequence, a hydrogen explosion occurred which blew out the upper blow-out panels of the reactor building. Also during drywell venting, some radioactive gases (including radioactive Iodine-131 and Cesium-137) were released to the atmosphere, but it was found to be a relatively small amount. Some contamination of food and drinking water has been reported.

The plant operator, Tokyo Electric Power Company (TEPCO), injected seawater and boric acid into the reactor vessels of these three units, in an effort to cool the fuel and ensure that the reactors remained shut down.

Later, seawater was delivered to the containment systems to fill the region below the RPV (For the Mark-I containments, up to the height of the main vent pipes to the pressure suppression pool, about ½ m. Water was also injected into the RPVs, but some water leaked into the primary containment vessels, i.e., PCV. However, the water in the PCVs never reached the bottom head of the RPVs). The intent of these actions is to promote cooling of any corium, which may be released from the RPV, prevent failure of the steel containment liner, scrub any radioactive aerosols formed during concrete ablation by the corium, and help reduce the potential for a hydrogen explosion within the containment. Nevertheless, the novel feed-and-bleed method being used for core cooling appears to have been helpful, but it requires that the steam formed due to boiling in the core be periodically vented and replaced with cold salt water.

Compounding the challenges with cooling the reactor cores at Units 1, 2, and 3, the integrity of the spent fuel pools (i.e., large open pools resembling swimming pools) at Units 1, 2, 3, and 4 has also been a concern.

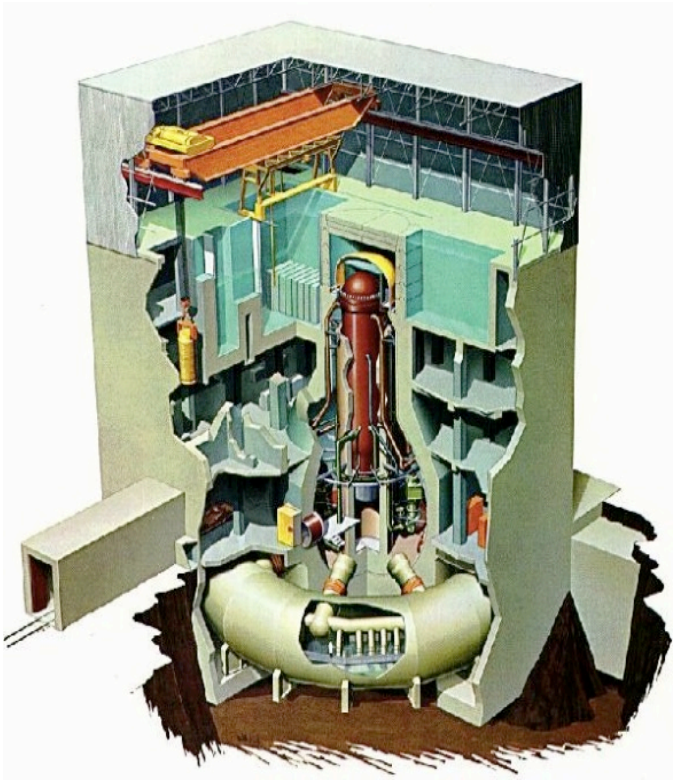


**Figure 1. Mark-I containment similar to Daiichi Nuclear Power Plant**

**Principal Technical Issues**

Some key safety issues observed from Fukushima Accident are summarized as follows.

**BWR Mark-I Severe Accidents**

During a severe accident in a BWR with a Mark-I containment, the dominant containment failure concerns are from 1) over pressure from steaming and 2) drywell shell melt-through caused by direct contact with core debris. If containment heat removal system fails, venting is the preferred option. The containment atmosphere is inerted with nitrogen to prevent a combustion event from potential releases of hydrogen.

The preferred approach to prevent drywell shell failure by direct contact with core debris involves flooding of the drywell cavity; however, the availability of containment heat removal systems is still required for long-term stability. Water in this scenario cools the core debris and limits concrete erosion (and related gas generation) so that steam is the main driving force for containment pressurization. The drywell spray and containment heat removal systems are designed to condense steam and remove heat from containment and therefore can control the containment pressure under these circumstances.

**Probability Risk Assessment**

The U.S. Nuclear Regulatory Commission (NRC) cited core-melt frequency estimates from probabilistic risk assessment (PRA) studies in the ranges from $2\times10^{-5}$ to $1\times10^{-4}$ event/reactor-year, *i.e.*, from 1 to 5 per 10,000 reactor-years; and for Peach Bottom Unit 2, a GE BWR with a Mark-I containment, $1.202\times10^{-5}$, *i.e.*, 1 in about 10,000 reactor-years. Thus, the historical frequency of core melt accidents worldwide shows significance of severe accident in safety of the power plants.

**Station Blackout**

Previous studies sponsored by the U.S. NRC have concluded that the loss-of-offsite-power and station blackout accidents are important contributors to core damage frequency for BWR designs. Station blackout accidents involve an initial loss of offsite power followed by failure of the emergency onsite AC power sources. The failure of AC power sources results in failure of multiple mitigating systems, leaving the steam-driven systems, such as the RCIC and high-pressure core injection (HPCI) systems as the only safety-related engineered safety feature available for coolant injection.

**Spent Fuel Pools**

The spent fuel pools are not located within containment buildings. Rather, they are located above the containment in the reactor buildings. Throughout the recovery effort, it is essential to keep the spent fuel pool properly cooled and full of water, which can be done in several ways, including with a

fire hose. Although videos released from TECPO suggest that there is adequate water in these pools, the concern about these pools has led to renewed calls for long or intermediate storage issue of spent fuel.

**Scale of Accident**
The Fukushima accident clearly indicates that having multiple units in one location has the potential to increase radioactive source term during an accident.

**Hydrogen Generation and Fires**
During a severe accident, there is the possibility of hydrogen generation and escape to the containment environment. The release of hydrogen and its transport within the containment and auxiliary building can lead to ignition, which poses significant potential for explosions and breach of containment.

**Radiation Leakages to the Environment**
There are several leakage paths from a crippled reactor and spent fuel storage pool. The process of deliberate venting, depressurizing of vessel or containment may lead to radiation discharge to the environment. The coolant or contaminated water can leak through breaches in the containment to the ground, soil and ultimately to groundwater.

**Emergency Preparedness**
Emergency preparedness is a key element of a nuclear power plants defense-in-depth strategy to protect the public from the consequences of an accident. Emergency Operator Procedures and Severe Accident Management Guidelines are an integral part of emergency preparedness. They assign roles and responsibilities for the different members of the emergency response organization involved in accident management.

## Conclusion

In the coming years, these issues and others will be researched and scrutinized, resulting in many lessons learned. It is likely that regulations governing plant licensing will be revisited and, possibly, revised should new conclusions from these efforts so dictate.