THE *NUCLEAR NEWS* INTERVIEW

Fauske and Henry: On vapor/steam explosion analysis

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The book *Experimental Technical Bases for Evaluating Vapor/Steam Explosions in Nuclear Reactor Safety* was recently published by the American Nuclear Society. The authors, Hans Fauske and Robert Henry, say that the possibility of vapor/steam explosions occurring at nuclear power plants is an important consideration for safety assessments of events wherein a high-temperature molten mass could come into contact with a liquid coolant.

The authors stress that potential accident conditions involving these types of explosions must be evaluated in a manner consistent with the available experimental technical bases. Their new book, they say, provides a common reference that includes the total experimental database for vapor/steam explosions, as well as information directly related to molten materials and the coolant of interest.

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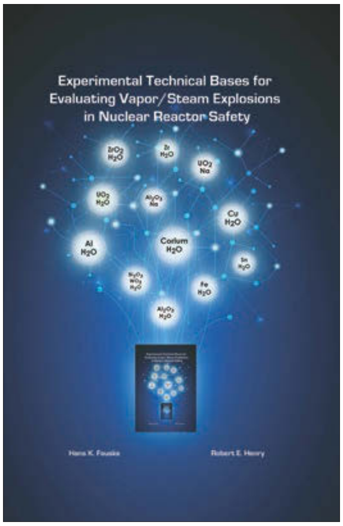
Henry: "Vapor explosions in general are an integral part of reactor safety evaluations."

Early in his career, Fauske joined Argonne National Laboratory, where he focused on reactor safety evaluations for both fast and light-water reactors. Vapor explosions were a key element of the safety evaluations for the Fast Flux Test Facility and the Clinch River Breeder Reactor designs, and steam explosions were an important part of the safety assessments for water-cooled reactors. Fauske left ANL in 1980 to establish, with Robert Henry and Michael Grolmes, Fauske & Associates. In 2011, Fauske stepped away from management responsibilities at the company to spend more time on engineering evaluations and writing.

Henry also worked at ANL, under Fauske's direction, on both fast reactor and LWR safety. In March 1979, the

Three Mile Island-2 accident occurred, and during the following summer and fall, Henry was on loan from ANL to the Nuclear Safety Analysis Center, which was established by the Electric Power Research Institute to study the data obtained from the accident. By that winter he was part of an ANL group that worked with Commonwealth Edison to conduct a near-term study on the implications of the TMI-2 accident for the Zion reactor, located north of Chicago, Ill. The issue of steam explosions was a major component of the Zion study. Henry also authored *TMI-2: An Event in Accident Management for Light-Water–Moderated Reactors*, published by ANS in 2011.



Through the years, Fauske & Associates has been deeply involved in nuclear and chemical reactor safety evaluations. The company developed the Modular Accident Analysis Program (MAAP), a computer code that runs faster than real time and can evaluate the response of boiling water reactors and pressurized water reactors for a broad spectrum of accident sequences. Steam explosion modeling is an important component of the MAAP evaluations.

Rick Michal, director of ANS's Department of Scientific Publications and Standards, conducted this interview with Fauske and Henry, whose new book is available through ANS and at Amazon.com.

Why did you write this book?

Henry: The book is needed by the nuclear community. Let me begin by explaining that a steam explosion is referred to as a vapor explosion when water is the volatile liquid that is vaporized. Vapor explosions in general are an integral part of reactor safety evaluations if accident conditions could lead to high-temperature molten fuel coming into contact with the liquid coolant. Both Hans and I have been active for more than four decades in developing the understanding of vapor explosions for different types of reactor designs. During this time we have had the opportunity to know and work with many talented, dedicated engineers and scientists who have touched on one or more of the numerous facets that comprise this phenomenon. In addition, we have had the opportunity to perform experiments, observe other experiments, and examine the relevant data that has been gained from programs conducted all over the world.

It has always been our conviction that any evaluation of vapor explosions for potential reactor accident conditions must be consistent with the entire experimental database that has been developed. To quote W. Edwards Deming, "Without data you are just a person with an opinion." The relevant data associated with vapor explosions now spans at least five decades, and some of the original papers, reports, conference proceedings, and other source materials are somewhat difficult to find, while some old reports exist only as copies that are virtually unreadable. Therefore, our first reason for writing the book was to define the technical bases by listing the key experiments, from our perspective, and then describing the test facilities and providing a summary of the experimental results. Equally important, the 19 pages of references in our book tell the readers where they can find more details on these experiments should they have a desire to read the original documents.

Fauske: A second but related reason for the book is that we have observed that many of the original experiments don't seem to be referenced in some of the more recent papers, even when comparable results have been obtained. This can be for many reasons, such as that the authors may not be aware of some of the original experiments, the original documents have been difficult to find, or the authors documenting some of the more current works didn't have time to develop an in-depth understanding of the original documents. Whatever the reason, this experimental database is too broad and too important to reactor accident evaluations and severe accident management guidelines to be minimized. As a result, we wrote the book to provide a convenient, common reference for experimentalists or analysts to ensure that they are consistent with the broad experimental technical bases given in the book when they are planning their respective approaches to vapor explosion experiments or models and when they are documenting their results.

Henry: A third reason for this book is that we have found through this growing experimental basis that the major observations have consistently demonstrated a few important behaviors that have different characters, depending on the reactor design in question. For the liquid sodium–cooled fast reactors, the general behavior principles for a vapor explosion (explained in Chapter 2) that are completely consistent with the experimental bases lead to a set of requirements for a large-scale vapor explosion that could not be satisfied under accident conditions. For commercial water-cooled nuclear reactors with oxidic fuel and zirconium alloy fuel pin cladding, the experimental bases (discussed in Chapters 3 and 4) that are derived from numerous experiments throughout the world show only very weak events, and these can be characterized in a simple, bounding manner for severe accident analyses. Chapters 5 and 6 discuss those experiments that are related to the role of aluminum in water-cooled reactors such as were observed in the BORAX-I and SPERT-I tests, as well as the accident that occurred in the SL-1 reactor. High-temperature molten aluminum is a very reactive metal in the presence of steam.

These components of the experimental databases address the mechanisms and the necessary conditions for a steam explosion to transition into a chemical explosion. These are particularly relevant to special-purpose reactors that differ greatly from those just mentioned but nevertheless have aluminum structures in a water-cooled reactor. Consequently, these need to be considered in light of the possibility of a steam explosion alone, as well as the possibility, or lack thereof, for an explosive chemical reaction to be initiated.

Is the book intended to address the severe accident analysis for all liquid-cooled reactors and not just commercial nuclear power reactors?

Henry: Yes. Severe accident analyses must consider those conditions that could cause the reactor fuel to become molten, which generally means very high temperatures, and then come into direct contact with the liquid coolant. This applies to all reactors with a liquid coolant in which accident conditions could result in very high fuel temperatures and includes water-cooled commercial power reactors, liquid metal–cooled fast reactors, and special-purpose reactors.

Could you list the conditions or requirements that could lead to a vapor/steam explosion?

Fauske: First, there must be a liquid-liquid system in which the high-temperature liquid comes into direct contact with the colder, more volatile liquid. Second, experiments show that the high temperature of the hot liquid must be greater than a specific temperature for the vapor nucleation rate to be of sufficient magnitude to generate a significant shock wave. In addition, experiments show that the temperature of the hot liquid must be sufficiently high such that the contact temperature is equal to, or greater than, the spontaneous temperature of the coolant. This spontaneous nucleation temperature approaches, or is equal to, the homogeneous nucleation temperature of the coolant. These three points are discussed in Chapter 2. And last, the ambient pressure surrounding the liquid-liquid system must be less than the minimum pressure that can prevent the occurrence of an explosive interaction, as is discussed in Chapter 3.

Could you expand on why there is such a strong emphasis on the experimental database?

Fauske: While the phenomenon of vapor explosions is a physical process that has been part of severe accident evaluations for decades, there are many different designs that need to be evaluated with respect to whether or not such an event could occur, and if it could occur, what the energy released by the explosion would be. The answers to these two questions are design dependent, and each design should have a relevant technical basis to illustrate the influence of the design, as well as the range of possible severe accident conditions. Experimental evidence is essential to confidently cover the extent of such conditions.

The central thesis of the book is that any representation of vapor/steam explosions must be consistent with the body of experimental work reported in the literature. What are the key scientific principles that are demonstrated by the composite experimental works?

Henry: The key principles are the mixing of the high-temperature melt and the coolant to a size scale for the melt of about a centimeter in diameter. For a vapor explosion to occur, there must be nucleation of liquid to vapor and rapid energy transfer to generate vapor faster than the surrounding medium can respond to the rapidly increasing steam volume. Of these, the method of vapor nucleation from the liquid state is the most important. It differs by orders of magnitude from the normal boiling processes that experience nucleation at imperfections—for example, crevices, scratches, and pits—in the solid surface for a liquid-solid boundary, such as a pot of water on a stove or a fuel rod surface transferring energy to the water coolant.

In addition, the instantaneous vaporization rate is orders of magnitude greater than the well-known critical heat flux process for steady-state boiling behavior. For a vapor explosion, the nucleation sites are formed at a liquid-liquid boundary that has no such imperfections, and, as a result, much higher coolant temperatures are required for nucleation to occur. Once these temperatures are reached, however, the density of the nucleation sites quickly becomes enormous. This produces the immense steam generation rate that forms a shock wave and the explosive behavior.

> ***“The experimental database includes numerous in-reactor and out-of-reactor experiments where high-temperature molten oxidic materials were poured into sodium with no initiation of large-scale vapor explosions.”***

There are many types of nuclear reactors in the world. How do these principles relate to various types of reactors?

Henry: The basic vapor explosion general behavior principle—that the contact interface temperature must equal or exceed the coolant spontaneous nucleation temperature—would not be satisfied for the accident conditions of a liquid metal–cooled reactor. Thus, large-scale vapor explosions could not be initiated. For commercial water-cooled reactors with oxide fuel and zirconium alloy fuel pin cladding, the interface temperature principle is satisfied, but the experimental results discussed in Chapters 3 and 4, which are from numerous experiments that were performed in different laboratories in different countries, show either no explosive interactions or only very weak events if they could be initiated. Equally important, these can be characterized in a bounding manner for severe accident analyses using a simple theoretical representation for the energy transfer. It should be noted that the interface temperature principle is also satisfied for the molten aluminum-water system discussed in Chapters 5 and 6.

Several times both of you have emphasized that the important experimental observations have been documented in laboratories throughout the world. Can you give some examples of the extent of the experimental database for the key principles mentioned previously?

Henry: The importance of the interface temperature principle is clearly illustrated by experiments performed at Argonne National Laboratory using simulant materials. These are further supported by the experiments where high-temperature solids dropped into water did not produce a steam explosion. In addition, the experimental database includes numerous in-reactor and out-of-reactor experiments where high-temperature molten oxidic materials were poured into sodium with no initiation of large-scale vapor explosions because the contact interface principle was not satisfied due to the thermal properties of sodium. This further supports this principle.

Fauske: Numerous experiments have been performed with different liquid-liquid mixtures and at different scales to demonstrate the influence of ambient pressure on the capability to initiate a vapor explosion. Simulant fluid experiments at ANL first demonstrated this influence, and additional confirmatory experiments were performed with molten salt and water (a very explosive liquid pair) in the test facilities at the ISPRA laboratory in northern Italy. Furthermore, additional small-scale experiments on the growth rate of vapor bubbles that are initiated by homogeneous nucleation have also clearly shown the influence of pressure. All of these contributions demonstrate this important behavior that could be influential for some accident conditions in water-cooled power reactors.

As we all know, there have been accidents at Fermi-1, Three Mile Island-2, Chernobyl-4, and Fukushima Daiichi. Were any important lessons taken from these accidents that confirm/supplement the experimental database?

Fauske: The liquid sodium–cooled, metallic uranium–fueled Fermi-1 reactor experienced the melting of parts of three fuel assemblies. Considerable molten material came in contact with the liquid sodium coolant, but there was nothing in the accident record or the defueling process that indicated anything like a vapor explosive behavior. This is consistent with the experimental database.

Henry: For Three Mile Island, the pressure in the reactor vessel when molten core materials drained into water was much greater than the minimum pressure that experiments (and analyses) have shown would have prevented a steam explosion. So, the accident behavior is consistent with the experimental database.

The Chernobyl RBMK design was a water-cooled, graphite-moderated reactor that had a positive void reactivity coefficient. This was a design that was much different from the BWRs and PWRs operated in the United States and elsewhere in the world. This design, combined with the sequence of events that preceded the initiation of the Chernobyl accident, led to a core condition in which the core was rapidly overheating and boiling away the available water inventory. With the positive void reactivity, this induced a rapid increase in the core power. The USSR's report on the accident estimated that the core power reached 500 times the peak operating power over several tens of seconds. Consequently, the explosion that occurred in the accident was due to a large pressurization of the reactor system that eventually ruptured and discharged radioactive fission products to the environment. This was not a steam explosion.

All three of the Fukushima Daiichi reactors that experienced severe core damage were depressurized during the accidents. In these accidents, steam explosions were not prevented by elevated pressures, so potentially they could have occurred. Most certainly there were hydrogen explosions in the various reactors. The evaluations of the plant data, however, and the robotic excursions into the containments of Units 1 and 2 have shown no indication of any damage or any other observation that could be attributed to a steam explosion event. This was consistent with the very weak events that have been observed in experiments with oxidic core materials. In this regard, it should also be noted that even these weak events have been observed only when they are triggered by explosive external triggers, such as blasting caps or exploding wires.

Since the strength of a steam explosion would be determined by the amount of molten core material mixed in the water, what controls how much molten material could be mixed with the coolant for water-cooled reactors?

Fauske: Experiments show that when the molten material drains into water, it breaks up into capillary-size droplets, about 1 cm in diameter, and, simultaneously, steam is generated due to film boiling—very slowly compared to the generation rate during an explosion—around the droplets. As molten material increases, more steam is formed, and multiple experimental programs show that eventually the water can be dispersed by the steam flow. When this is reached, no additional molten debris can be mixed into the water. With the high melting temperature of molten uranium dioxide, or molten mixtures of core materials (corium), the steam generation rate needed to disperse the water typically requires only a very small fraction of the core inventory, typically less than 1 percent.

What determines if a steam explosion could transition into a chemical explosion?

Fauske: If a high-temperature reactive molten metal is poured into water, the metal-water reaction releases hydrogen. There are two controlling features: First, the solubility characteristic of hydrogen in the molten metal as a function of temperature, and second, the metal temperature. If the metal solubility increases with temperature and the metal temperature is sufficiently high, a significant quantity of the hydrogen that was generated can be dissolved in the metal. If the local metal-water contacts escalate into a steam explosion or are forced into contact by an external explosive trigger, the rapid cooling induced in the molten metal results in supersaturation of hydrogen, which then rapidly exits the solution, causing fragmentation of a thin layer of molten aluminum that is dissolved by the hydrogen. These fine-scale molten metal fragments rapidly oxidize in the steam, initiating a much more energetic chemical explosion.

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You mentioned that this book summarizes the technical bases and provides a common means to discuss and address this issue for various designs. Could you discuss how vendors, utilities/operators, and regulatory agencies could perform their evaluations for the different types of reactors?

Henry: The differences in reactor designs require that the information from the experimental technical database be applied in a different but consistent manner for each design. For example, the spectrum of accident conditions for liquid metal reactors that are oxide fueled does not satisfy the interface temperature principle. Furthermore, the metallic uranium and/or mixed uranium-plutonium metallic-fueled reactors would melt and shut down long before they would be at a sufficient temperature to satisfy that principle.

In another example, light-water– and heavy-water–cooled commercial nuclear power reactors satisfy this interface temperature principle, but the database shows that the conditions of rapid melt freezing due to the thermal radiation–dominated film boiling and the thermal properties of oxide fuels result in a very low efficiency (conversion ratio) for thermal explosions. Combining these, one finds that the damage potential for steam explosions is very small. Moreover, the database also shows that any attempt to drive the molten materials together at high velocity causes localized entrainment and quenching such that no significant molten core material was accumulated within the water.

A third example is that special-purpose reactors can be fabricated with differently designed fuel, constructed with other materials, and have substantially different operating parameters. Each design needs to be evaluated individually. This also means, however, that the possibility of rapid chemical reactions that could cause a steam explosion to transition into a chemical explosion would need to be considered for water-cooled reactors that would use highly reactive metals with a hydrogen solubility characteristic that increases with temperature.

Fauske: Essentially, there are three types of organizations that need to consider the possible role of vapor/steam explosions for individual designs: the reactor vendor/designer, the operating organization—for example, a utility, national laboratory, industrial laboratory, or university—and the regulatory agencies. Of these, the reactor vendor needs to address the design of interest. The operating organization may have more than one design under its responsibility, and the regulatory agency needs to have a consistent methodology that is applied to all designs under its purview. With varying needs for consistency in the approach, each organization has somewhat different needs for the experimental database.

An illustration of how the experimental bases need to be understood and used is the SL-1 accident that occurred in January

1961, early in the life of commercial reactor programs. The accident is discussed in the book, but here it is sufficient to note that the reactor was fueled with metallic uranium-aluminum alloy fuel with aluminum cladding and cooled by water. The accident was due to a fast reactivity ramp rate induced by an undefined maintenance error. A steam explosion resulted, which also had a chemical component that caused major damage to the reactor and fatally injured the three-man operating crew. (Chapter 6 provides a discussion and evaluation of the accident, as well as evaluations of the BORAX-I and SPERT-I reactor experiments.) At the time of the Reactor Safety Study (WASH-1400), the sequence of events associated with the SL-1 explosion was used to structure a conservative probabilistic approach to the possible radiological consequences of a commercial reactor accident. The experimental technical bases now define the importance of aluminum in the accident, as well as the equally influential reactivity ramp in terms of melting the fuel within a fraction of a second, in the presence of water, and driving the fuel temperatures to values in excess of 1,400 K.

Henry: With this knowledge base, a reactor vendor for a water-cooled commercial power reactor could begin to address the steam explosion issue by stating, "Our design has no aluminum in the reactor core, and it is impossible to melt the oxide fuel in the presence of water." From this foundation, the vendor's evaluation could progress to how an accident sequence could melt fuel, how rapidly the molten core materials could be brought in contact with water, how much molten material could be "coarsely mixed" with water, and what the bounding energy release from such an interaction would be.

An operating organization would likely use the experimental bases in much the same way for a power reactor, but if the organization were responsible for a special-purpose water-cooled reactor with aluminum in the core, there would be a need to evaluate which accident sequences could melt the fuel and what the maximum temperature of the fuel would be in the presence of water. Would it be essentially the melting temperature of the fuel, or could it be significantly greater? The peak temperatures of the fuel and the extent of rapid oxidation in a steam explosion would need to be assessed for such designs.

Regulatory agencies may or may not have all three types—liquid-metal reactors, commercial power reactors, and special-purpose reactors—within their purview. As a result, those individuals responsible for severe accident evaluations within the agency would need to be familiar with and use the entire experimental basis in a consistent manner. **NN**