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An evolution of understanding of reactor pressure vessel steel embrittlement

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ABSTRACT

This paper attempts to summarize the lifetime contributions of Prof. G. Robert Odette to our understanding of the effects of neutron irradiation on reactor pressure vessel steel embrittlement. These contributions span the entire range of phenomena that contribute to embrittlement, from the production and evolution of fine scale features by radiation damage processes, to the effects of this damage microstructure on mechanical properties. They include the development and application of unique and novel experimental tools (from Seebeck Coefficient to Small Angle Neutron Scattering to confocal microscopy and fracture reconstruction), the design and implementation of large multi-variable experimental matrices, the application of multiscale modeling to understand the underlying mechanisms of defect evolution and property change, and the development of predictive methodologies employed to govern reactor operations. The ideas and discoveries have provided guidance worldwide to improving the safety of operating nuclear reactor pressure vessels.

1. Introduction

This is one of a series of papers presented at two special sessions of the Annual TMS Meeting in February of 2009 to honor the contributions of Prof. G. Robert Odette to the field of nuclear materials in general and to reactor pressure vessel steels and fusion reactor materials in particular. This paper addresses his contributions to the former. While the body of work in either of these areas would be a proud lifetime accomplishment for any scholar, Prof. Odette's contributions to materials science in general go beyond these two areas, including but not limited to extensive work in the area of hydrogen attack in carbon and Cr–Mo steels e.g. [1,2], and ductile phase toughening in brittle matrix composites e.g. [3–6]. On top of all this, he has made significant contributions to UC Santa Barbara in both the Academic Senate and various administrative roles as well as teaching and student mentoring, a sum total of accomplishments that is nothing short of phenomenal.

I have had the good fortune to know Prof. Odette in a variety of capacities: as a former student, a mentee and a colleague for 32 years. We have collaborated on numerous research programs and co-supervised a series of terrific graduate students, post-doctoral scholars and technical staff. Hence, it is my honor and privilege to provide an overview of his contributions to reactor pressure vessel (RPV) steel embrittlement.

2. A little history

Prof. Odette began his career as a Ph.D. student at the Massachusetts Institute of Technology, where he worked with Prof. Thomas Ziebold developing damage parameters in iron [7,8]. Here a change in property ΔP (e.g., increased yield strength) is related to a neutron spectrum $\varphi(E)$ by a damage parameter $G(E)$, which can be found from measurements of ΔP obtained from post-irradiation experiments and $\varphi(E)$ from neutron dosimetry. Hence, Prof. Odette gained early knowledge of tools that would last him throughout his career: dosimetry, in-reactor experimental methods, post-irradiation testing, and spectral analysis.

When he came to UC Santa Barbara (UCSB) as an assistant professor in 1970, he developed early relationships with a number of scientists at what was then the Hanford Engineering Development Lab (HEDL). They were productive collaborators in advancing his interests and expertise. These included Bill McElroy in the area of damage unfolding and dosimetry [9,10], Bob Simons in the area of dosimetry and damage function analysis [9,10] and Don Doran in the area of damage functions and defect production [10,11]. He also quickly picked up several graduate students at UC Santa Barbara in parallel efforts. He worked with Dave Schwartz in displacement modeling [12,13] and Dan Frey in developing models to relate radiation damage microstructure to macroscopic property changes [14]. As an undergraduate student at UC Santa Barbara in those early days, I worked with Prof. Odette to develop an experiment to measure sputtering rates in a variety of materials. I left to attend graduate school, and by the time I returned to UC Santa Barbara as an assistant professor, Prof. Odette had already developed a strong interest in reactor pressure vessel steel embrittlement.

With his basic interest and expertise in radiation damage production, microstructural evolution and mechanical property change, he began to develop specific interests in the area of light water reactor pressure vessel steel embrittlement. His interactions with researchers at HEDL led him to George Guthrie, with whom

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he built a collaboration on pressure vessel embrittlement correlation development that ultimately became the basis for Regulatory Guide 1.99 Rev 2. He intersected with a small start-up in Santa Barbara, Fracture Control Corporation (FCC), which nucleated around instrumented Charpy testing and led to a strong collaboration with its founders, Dick Wullaert and Bill Oldfield, in fracture of pressure vessel steels and data base development. Bill Sheckerd and Bill Server, then employees of FCC, were also instrumental in developing Prof. Odette's interests in fracture mechanics, and Bill Sheckherd ultimately moved to our research group and was key to developing our capabilities in the area of fracture testing. These relationships ultimately led to an intersection with Ted Marston and Karl Stahlkopf [15] at, what was then, a growing Electric Power Research Institute (EPRI), ultimately leading to a round of EPRI funding that helped launch the UCSB research program in RPV embrittlement.

3. The framework

Stemming from his early work, over the years Prof. Odette has developed a tool kit of abilities that render him a rather unique researcher in the field. His interest and expertise include in-reactor testing, primary defect production, damage microstructure evolution, mechanical testing, and dosimetry and analysis. But on top of this broad range of experimental, theoretical, and analytical skills, he brings an extraordinary insight. He is able to quickly grasp the technical relevance and importance of observed or predicted phenomena. He has been a pioneer in linking the very small (e.g., radiation induced defects) to the very large (fracture of a full sized reactor pressure vessel). And he has been a leader in demonstrating the importance of developing correlations of materials behavior – e.g., transition temperature shifts in irradiated steels as a function of metallurgical and environmental variables – within a physically-based framework that can be rigorously tested against data from well designed experiments as well as operational data bases. He also has personal traits that have assisted him, including an incomparable perseverance in determining the understanding of observed phenomena, and an ability to bring order and sound physical understanding from an abundance of conflicting and confounding data. And for Prof. Odette, there is never enough data.

This has all led Prof. Odette to be the major proponent of a multiscale modeling and experimental approach to characterizing reactor pressure vessel steel embrittlement. This is illustrated in one of Prof. Odette's many characterizations of this in Fig. 1. Here, modeling moves: (1) from characterizing defect production and early evolution by atomistic methods like molecular dynamics and lattice Monte Carlo techniques; (2) to defect population and composition evolution, employing thermodynamics and rate theory kinetics; (3) to determining the effect of the evolving damage microstructure on mechanical properties – for example, yield stress increases as predicted by computer modeling of dislocation-obstacle interaction and dislocation theory; (4) to finite element modeling (FEM) of crack tip fields combined with local fracture parameter theory to predict fracture toughness as a function of changes in the constitutive relation. In parallel, and in interactive reconciliation/calibration with results from the modeling effort, experiments move: (1) from characterizing irradiation induced defects – size, number density, character, composition – by a variety of techniques (transmission electron microscopy (TEM), Small Angle Neutron Scattering (SANS), atom probe, positron annihilation spectroscopy ...); (2) to characterizing changes in constitutive behavior (stress (σ)–strain (ε)), as a function of metallurgical and environmental variables in conjunction with the corresponding damage microstructure; (3) to characterizing fracture toughness as a function of temperature ($K_{Ic}(T)$) and shifts in transition temperature (Charpy and/or fracture toughness). This basic understanding, co-calibrated between models and experiment, then provides a mechanistic basis for crafting a correlation between an operational variable of interest – e.g., transition temperature – and the intrinsic and extrinsic variables that drive changes in it; and the resulting correlation can be validated against both experimental and operational data bases.

Embedded at the front end of this multiscale approach is another concept that Prof. Odette has developed and promoted. This is the concept of a computational microscope, illustrated in Fig. 2. As noted above, this involves parallel efforts in several areas. One is to characterize radiation induced defects by a variety of techniques. Each technique provides some, but not complete information about a defect: size, character, number density, volume fraction, composition, etc. By combining techniques, a more complete picture of a particular type of defect is obtained. Theory (e.g., thermodynamics and kinetics) and modeling (e.g., atomistic simulations) provide an additional picture of defect production and evolution. The predicted defect population can be combined with the theory underlying a particular microstructural characterization tool (e.g., scattering theory, electron diffraction, etc.) to predict the signature that a particular defect should exhibit for that technique. By requiring self-consistency among techniques, theory and signature, defects can be identified, well characterized, and indeed predicted in advance of observation.

This approach has served the community well, and Prof. Odette has made numerous contributions to the understanding of RPV embrittlement throughout this framework.

4. Contributions

In this section, I will attempt to provide an illustration of the range of contributions Prof. Odette has made to RPV embrittlement. Rather than list them in chronological order, I felt it was more fitting to describe them within the context of the multiscale modeling/experiment approach described above that he has been so instrumental in developing and promoting.

Working with co-workers (largely Maroudas and Wirth), Prof. Odette has applied molecular dynamics modeling and lattice Monte Carlo (LMC) techniques to follow the evolution of radiation induced and enhanced defect formation in iron and iron alloys [16–25]. This is illustrated schematically in Fig. 3. From post-cascade configurations of self-interstitials (SI) and vacancies, he and his co-workers have examined the formation and mobility of SI clusters, vacancy clusters and vacancy–copper atom clusters [16–21,25]. They have characterized the lifetime of vacancy clusters with and without copper atoms present, and demonstrated agreement with post-irradiation and in-reactor experimental data pertaining to the formation and dissolution of a component of the damage microstructure deemed as unstable matrix defects, believed to be vacancy-rich agglomerates [18,21–23]. The work has also demonstrated the formation of Cu-rich precipitates in Cu dominated solutions of Ni–Mn–Cu–Si in Fe, and the formation of Ni–Mn rich precipitates in low Cu solutions [24]. These latter, so-called late blooming phases, were predicted well in advance of their detection by microstructural characterization tools, and are of concern to the extended life of low-Cu steels currently in service.

Prof. Odette has coupled the atomistic simulations with thermodynamic and kinetic (rate theory) modeling of defect evolution. Indeed, in one of his earliest papers with Sheeks [26] they predicted the formation of vacancy–Cu complexes in displacement cascades, and this was confirmed over 20 years later by positron annihilation studies. This paper also laid out a host of issues that turned out to be critical to the evolving understanding of radiation hardening and embrittlement in RPV steels. Shortly thereafter, he authored the first journal paper [27] modeling accelerated precip-

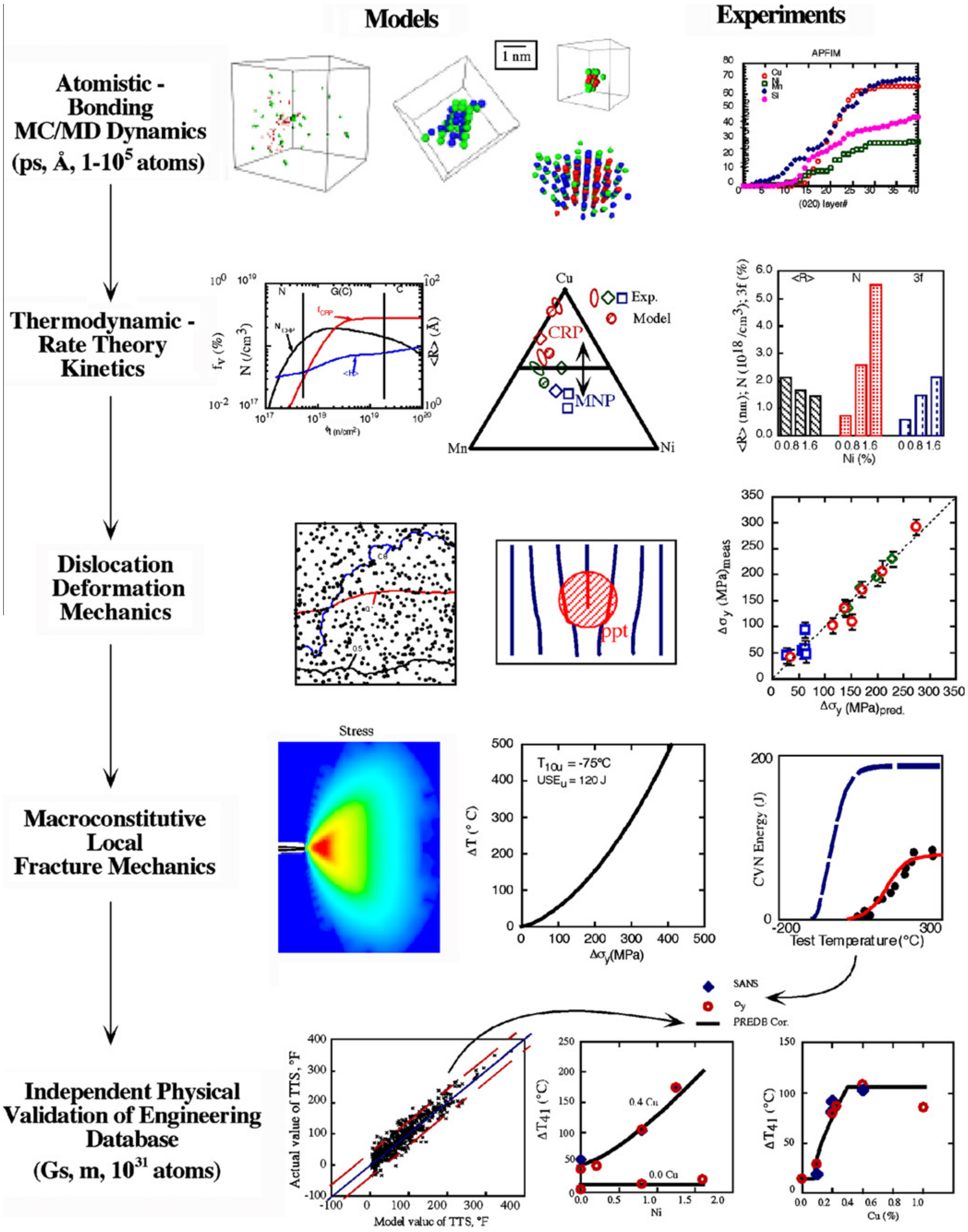

Fig. 1. Illustration of multiscale modeling and experiments to understanding and characterizing reactor pressure vessel steel embrittlement.

itation hardening by copper rich precipitates as a consequence of radiation-enhanced diffusion, ultimately leading to the mathematical framework for Nuclear Regulatory Commission Regulatory Guide 1.99 Rev. 2. As illustrated in Fig. 4 he has modeled the compositional evolution of precipitates in Fe containing Cu, Mn, Ni and other elements thought to play a role in radiation-enhanced precipitation process in RPV steels. From calculations of the chemical potential of each of the elements in solution and in the precipitate, allowing for solutes to migrate to the precipitate until their chemical potentials equilibrate between precipitate and solution, and accounting for a surface energy contribution to the free energy of the precipitate, predicted compositions of precipitates have been found to be in very good agreement with experimental observations [28–30].

Prof. Odette has also contributed to the development of an array of techniques used to characterize the radiation damage microstructure in RPV steels and model alloys. He was one of the first to use SANS to characterize both the size and volume fraction of radiation produced defects, and has continued to employ this technique extensively to the present [28–42]. Primarily using the neutron source and positional detector at the National Institute of Standards and Technology (NIST), his group built a facility for SANS measurements that employed a number of novel characteristics: (1) an automated, remote controlled sample changer to provide for numerous sample changes without having to access the beam tube; (2) a magnet that provided a strong, directional magnetic field in the specimen that allowed both magnetic and nuclear scattering components to be determined, the magnetic to nuclear scattering ratio permitting compositional evaluations; (3) a furnace to control specimen temperature, providing an opportunity to take specimens/precipitates through the Curie temperature to uniquely determine the magnetic character of the precipitates

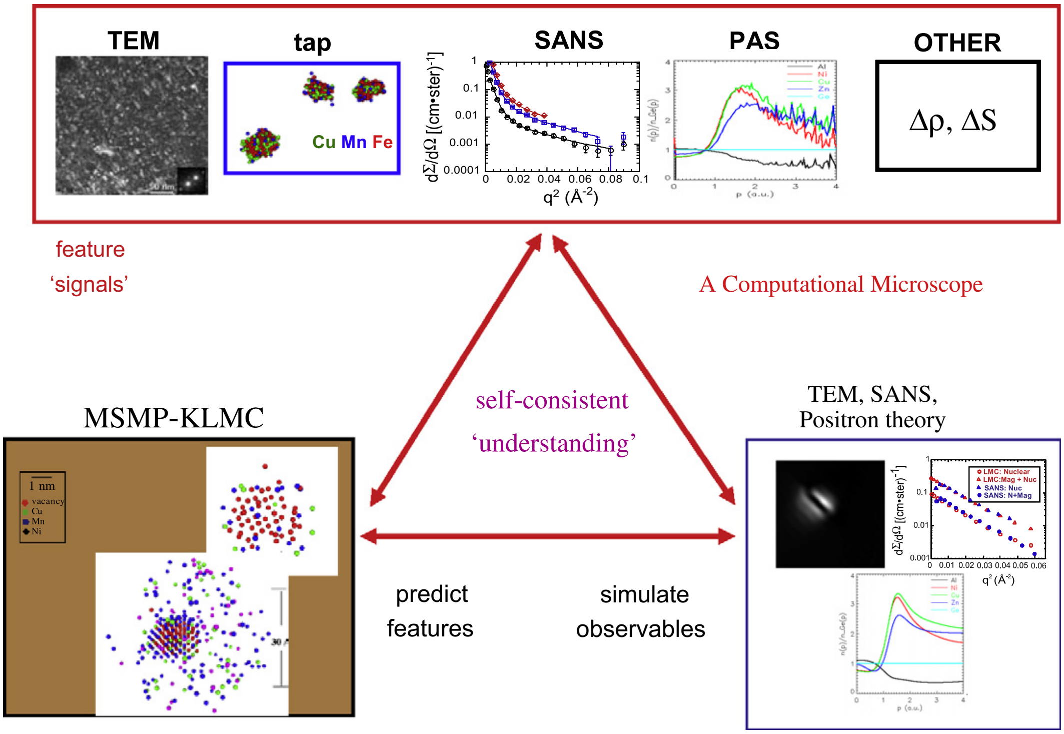

Fig. 2. Illustration of the concept of a computational microscope.

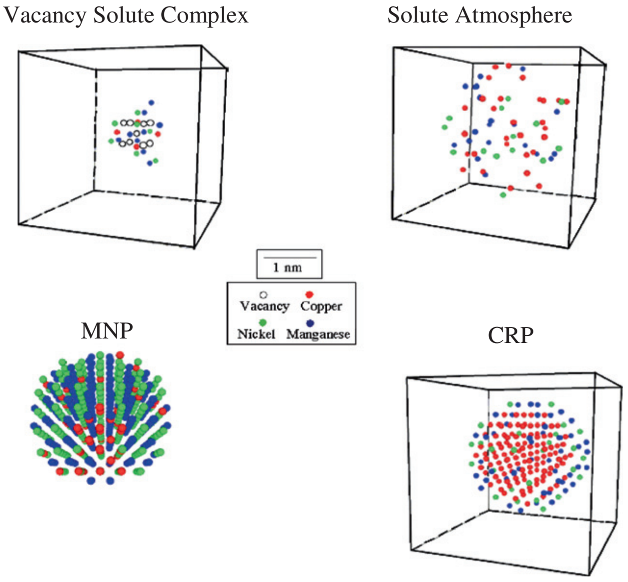

Fig. 3. Examples of defects predicted by atomistic modeling.

and demonstrate they were copper rich. SANS studies have been a mainstay of the UCSB program, providing a wealth of microstructural data on irradiated RPV steels and model alloys. Prof. Odette's early SANS studies demonstrated strong synergistic Cu–Ni–Mn interactions that not only lead to Ni–Mn segregation to Cu-rich precipitates but, in some cases, to Mn–Ni rich precipitates, validating the theoretical predictions of earlier work. As discussed later, the SANS microstructural data generated in this program have been combined with hardening models and post-irradiation hardening measurements to develop strong, robust relations between the radiation damage microstructure and mechanical property changes.

Restrictions on irradiation volumes available to the UCSB program, as well as personnel exposure considerations in post-irradiation testing, drove Prof. Odette and co-workers to develop a host of small specimen techniques to derive mechanical and microstructural data. Key to early work was the demonstration of quantitative relationships between changes in microhardness and changes in yield strength, allowing microhardness tests to serve as a means of tracking radiation hardening [43–45]. Moreover, UCSB developed techniques to automate microhardness testing on an array of specimens – primarily 3 mm diameter discs [46]. This not only provided an opportunity to test a large number of specimens – and hence to examine materials with many different compositions and exposure histories – but it also provided a means of accounting for variations in microhardness across the surface of a single specimen, allowing more precise measurement of microhardness changes. This approach was used to great advantage to measure not only radiation hardening, but changes in microhardness during post-irradiation annealing (PIA). This led to an extensive study of the recovery of radiation hardening during PIA as a function of composition, radiation history, and PIA temperature [46–48]; and these results were key to verifying the existence of several classes of defects produced during irradiation, as the vacancy agglomerates, or unstable matrix defects, annealed out at lower temperatures and shorter times than more stable defects, like radiation produced precipitates. This is illustrated in Fig. 5.

Prof. Odette was also an early adopter of using thermo-electric effects and resistivity measurements to track the amount of solute in solution as a function of irradiation or thermal history [49]. This approach, coupled with the constraint of mass balance, has been used to follow the precipitation process for a large number of materials with systematic variations in composition (Cu, Ni, Mn, Mo, Si, ...) as a function of both irradiation (flux, fluence, irradiation temperature) and thermal aging (at temperatures as low as 290 °C) e.g., [49–52].

He has also contributed to or employed other techniques through collaborations [27,30,35,53,54]. For example, he has inter-

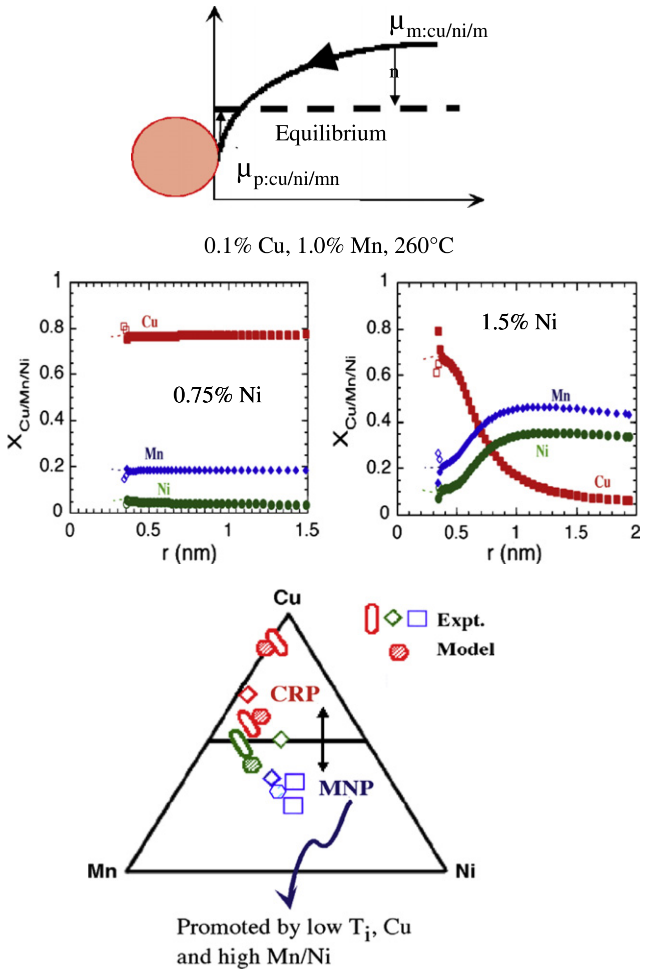

Fig. 4. Illustration of thermodynamic calculations of precipitate compositions from equilibration of solute chemical potentials between matrix and precipitate. The tertiary diagram compares predictions with experimental observations.

acted with Mike Miller at ORNL to employ atom probe techniques to characterizing irradiation produced defects [38,42]. He has been a central figure in trying to reconcile atom probe results with other techniques, like SANS and positron annihilation spectroscopy (PAS) [55–57]. SANS (and other) results suggest that copper rich precipitates in irradiated RPV steels have a copper rich core and a shell of other elements but little iron, while the early atom probe results suggested large amounts of Fe present in the precipitate. Prof. Odette's insistence on reconciling the results from different techniques has effected a number of improvements in the atom probe techniques, gradually bringing down the amount of Fe "detected" in the precipitates. Moreover, the work in PAS has verified much of the Cu–vacancy cluster behavior predicted from the atomistic simulations described above [55–57].

In keeping with Prof. Odette's early interests in microstructure–property relations, he has contributed heavily to our knowledge about how radiation damage microstructures in RPV steels effect hardening and embrittlement. As illustrated in Fig. 6, his early work in demonstrating quantitative relationships between hardness changes, yield stress changes, and Charpy transition temperature shifts [29,33,43–45,58] has been reinforced by later work laying out the theory underlying these relationships. He and co-workers have developed computer simulations of dislocations moving through a field of obstacles based on the work of Foreman and Makin [59], as illustrated in Fig. 7. The results of these simulations were used to develop a superposition law of the form [29,60].

$$\sigma_y = \sigma_{ys} + (1-S)(\sigma_{ym}^2 + \sigma_{yo}^2)^{1/2} + S(\sigma_{ym} + \sigma_{yo}) \tag{1}$$

where σ_y is the yield strength of a material containing two types of obstacles: pre-existing strong obstacles providing a contribution to yield strength σ_{yo}, and radiation-produced weaker obstacles providing a contribution to yield strength σ_{ym}; the superposition parameter S varies with the strength of the two obstacles and represents a combination of linear and root sum square hardening superposition. This has been extraordinarily successful in rationalizing both irradiation hardening and post-irradiation annealing data, where multiple defect populations evolve. He has also developed an extensive data base for verifying and calibrating the Russel-Brown hardening law [61], which is based on dislocation line energy (elastic modulus) differences between matrix and precipitate, and relates the volume fraction of a precipitate to yield strength. As noted above, the SANS data developed in the UCSB program over many years – accompanied by hardness and yield strength change measurements on irradiated, aged, and post-irradiation annealed specimens – have provided a robust calibration and verification of these models. This is also illustrated in Fig. 7.

Prof. Odette's interests in fracture in RPV steels led him to begin to implement finite element methods (FEM) to characterize crack tip stress and strain fields. He also began to look at developing local fracture parameter models based on the Ritchie–Knott–Rice (RKR) approach [62] to characterize the crack tip conditions leading to brittle cleavage fracture. In these models cleavage initiation occurs when a critical stress σ^* is exceeded over a critical dimensional scale ahead of the crack, such as a critical area A^* enclosed by a stress contour σ^*. A breakthrough came with the development and application of confocal microscopy and fracture reconstruction methods to experimentally observe damage evolution at the tip of a loaded crack [63,64]. Here the topography of two conjugate fracture surfaces are mapped quantitatively in three dimensions using a confocal microscope. The digitized fracture surfaces are then computationally overlapped back to the starting condition of the unloaded pre-existing crack; as the two surfaces are then computationally separated to simulate loading of the cracked specimen, the regions of separation – or damage accumulation – can be tracked and visually replicated. An example is shown in Fig. 8.

These results can be used in conjunction with finite element calculations to determine local fracture parameters like $\sigma^* - A^*$. This in turn can be used to determine size effects on fracture processes, and Prof. Odette and co-workers have developed an extensive set of calculations to examine the role of specimen width B and ligament size b on fracture toughness [65,66]. This calculational approach has in turn been used in conjunction with a very large test matrix to demonstrate and verify specimen size effects [66]. This matrix consisted of three-point bend specimens with systematic variations in B and b, from $B = 8$ mm to 254 mm and from $b = 3$ mm to 25 mm, as shown in Fig. 8. By combining finite element modeling (FEM)/local fracture parameter characterizations of fracture, the fracture toughness for each specimen geometry could be corrected to a value corresponding to small scale yielding (SSY), thus collapsing all the data onto a single curve as shown in Fig. 9.

This has served as a background for examining the fundamental underpinnings of the master curve (MC) approach [67] to characterizing the fracture toughness–temperature relationship of RPV steels, both at beginning of life and as a function of irradiation. As illustrated in Fig. 10, the MC is a fracture toughness-temperature curve $K_{Jc}(T)$ indexed in temperature space by a reference tem-

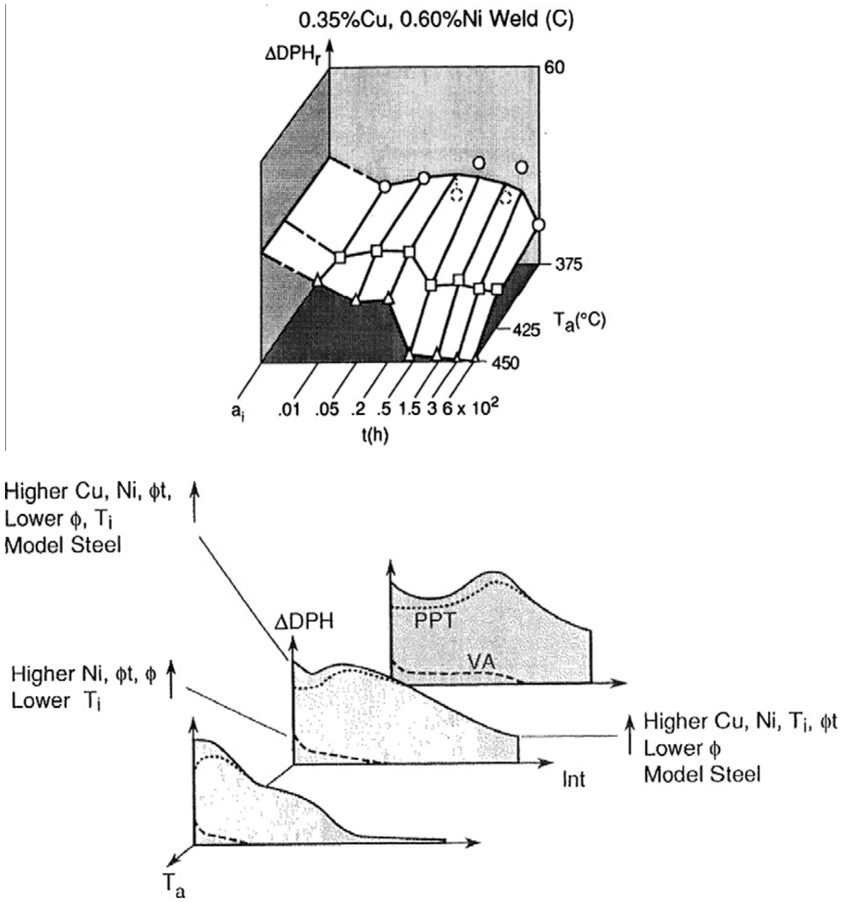

Fig. 5. Illustration of post-irradiation annealing data for a .35 Cu, .6 Ni weld annealed at three different temperatures. Schematic illustration of multi-defect contributions to the post-irradiation annealing hardness.

perature T_o which can be determined by a relatively small number of relatively small specimens. It is then shifted in temperature space by an amount ΔT, by environmental (e.g., irradiation) variables or test conditions (e.g., strain rate, specimen size/constraint). The work described above has contributed to determining both ΔT's for size/constraint effects as well as specimen size limitations in measuring T_o. Prof. Odette has also provided fundamental insight to the apparently constant shape of the MC. Local fracture parameter models – e.g., RKR – suggest that irradiation hardening should not only shift $K_{Jc}(T)$ to higher temperatures but should decrease the curvature of $K_{Jc}(T)$ as well. However, most experimental data to date supports the constant shape assumption. Prof. Odette argued that such a constant shape could be explained if the critical stress σ^* was temperature dependent. He then set out to measure $\sigma^*(T)$, developing a clever set of compound specimens where a single crystal of iron was embedded in a steel specimen, with a sharp crack penetrating the single crystal. These specimens were tested in a variety of configurations and load frames – including four point bend, and compression testing – to detect both crack initiation and crack arrest and measure the corresponding local toughness, hence critical stress, as illustrated in Fig. 11. Results to date indicate a temperature dependence of σ^* that rationalizes the constant shape of MC [68,69].

Prof. Odette has also played a leadership role in designing and implementing very large experimental matrices in which large numbers of alloys with systematic variations in composition and metallurgical state are conditioned in a set of well-controlled environments with systematic variations in environmental variables. Notable examples include:

(1) An EPRI-sponsored project in which over 100 commercial and model alloys were irradiated in a facility at the University of Virginia Reactor at three fluxes to three fluences at irradiation temperatures from 270 °C to 320 °C. Specimens included both mechanical property (microhardness, tensile, fracture) and microstructural (TEM, SANS) geometries [70].

(2) Several sets of High Flux Isotope Reactor (HFIR) irradiation experiments to systematically examine the effects of relatively low temperature irradiation (60–290 °C) on irradiation microstructure and hardening: more than 70 alloys were examined using both microstructural and mechanical property specimens [51,71]

(3) A set of DIDO irradiation experiments were combined with UCSB data to systematically examine the effects of flux on irradiation hardening and damage microstructure[72].

(4) An NRC-sponsored irradiation variables (IVAR) experiment at the University of Michigan Ford Reactor facility, in which over 80 alloys and 8000 specimens (again microstructural and mechanical property) were irradiated at three fluxes, three temperatures and overlapping fluences from 0.04–1.6×10^{19} n/cm^2. Alloys consisted of commercial, model commercial and model alloys with systematic variations in key compositional variables: Cu, Ni, Mn, Mo, Si ... [39]

Results from these large experimental matrices have provided key insights into the fundamental understanding of radiation embrittlement in pressure vessel steels as outlined below. In addition to these experiments, Prof. Odette was responsible for leading the effort in a set of large experiments to examine thermal aging

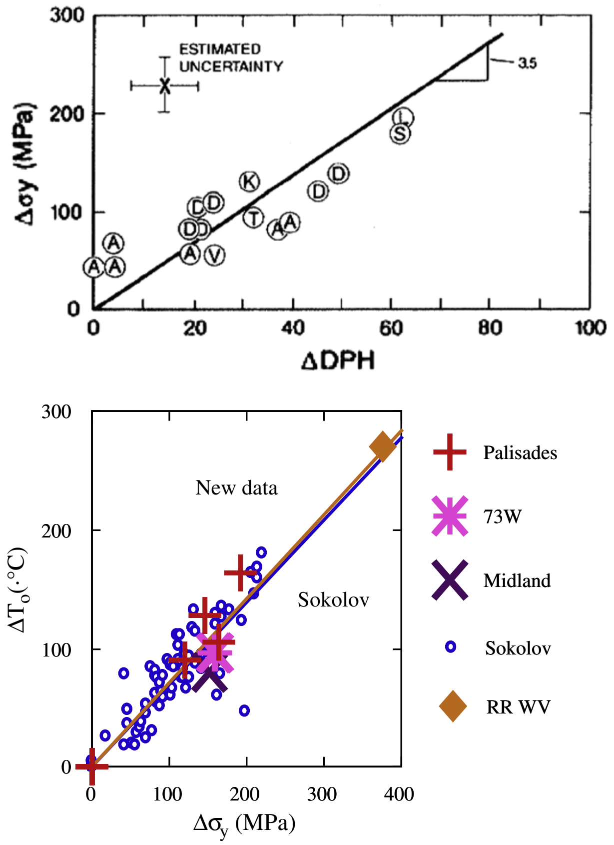

Fig. 6. Correlations between irradiation hardening measured by yield strength ($\Delta\sigma_y$) and microhardness (ΔDPH) changes; and between yield strength changes and shifts in the reference temperature (ΔT_o) for irradiated RPV steels.

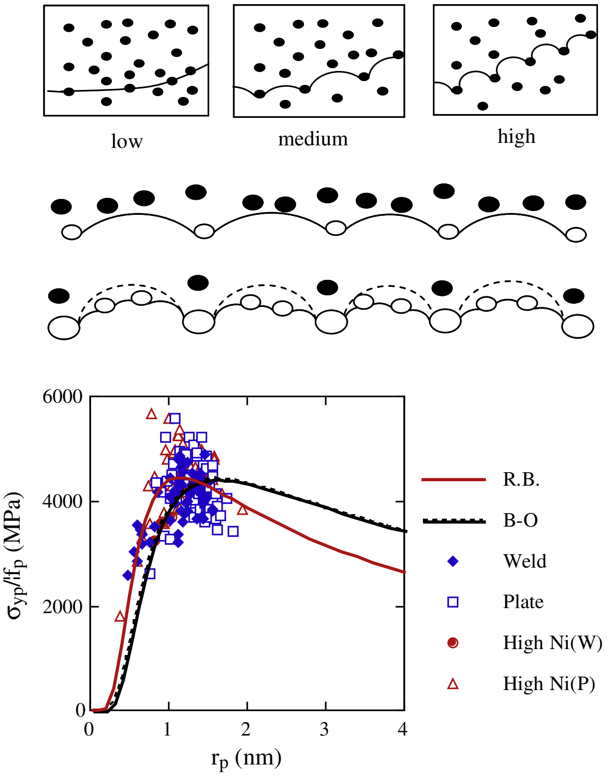

Fig. 7. Illustration of computer simulation of dislocation moving through fields of strong and weak obstacles. Comparison of predictions of hardening derived from the microstructure of irradiated RPV steels using the Russell-Brown (RB) model to experimental measurements.

[52] and post-irradiation annealing (as described above) [46–48], using a similar approach of a large number of materials with systematic variation in metallurgical variables and exposing a variety of specimen types to variations in aging/post-irradiation annealing temperatures and times.

The combination of theory, modeling, microstructural and mechanical property measurements on specimens irradiated/aged/annealed in these large experiments has led to a number of fundamental insights regarding the effects of extrinsic and intrinsic variables on radiation damage microstructures and properties. Although the following list is not comprehensive, it is representative of the range of insights in which Prof. Odette played a pivotal role:

(1) The development of robust models of irradiation hardening and transition temperature shift (TTS) in RPV steels based on the evolution of several predominant defect types in irradiated RPV steels, including precipitates (e.g., Cu rich for high Cu steel, Mn–Ni rich in low-Cu steels at high fluences), stable matrix defects, and unstable matrix defects (UMDs – vacancy agglomerates, partially affiliated with Cu and/or other alloys) [34–38,44,48,50,51,74–78]

(2) The evolution of the Cu–Ni–Mn precipitate population by radiation-enhanced diffusion processes and the employment of rate theory models calibrated with extensive data to predict that evolution [27–29,31,32,35]

(3) The role of Cu, Mn, Ni in mitigating the damage microstructure [31–35,45,50,71,73,74] – for instance:
   a. a threshold level of bulk Cu before the onset of hardening;
   b. an upper level of bulk Cu beyond which hardening no longer increases (due to pre-precipitation of some Cu during heat treatment prior to service);
   c. the attraction of Mn and Ni to the surface of Cu precipitates leading to Cu-Mn–Ni precipitates that depend on irradiation flux, fluence and temperature as well as matrix composition prior to irradiation.

(4) The role of thermo-mechanical treatment of RPV steels in mitigating their response to irradiation – e.g., the effect of heat treatment time and temperature on:
   a. Cu pre-precipitation, which mitigates the amount of Cu in solution prior to irradiation and thus available to contribute to radiation-enhanced precipitation hardening [31–34,39];
   b. dislocation densities, which serve as sinks for point defects, mitigating radiation-enhanced diffusion and precipitation processes [34,39];
   c. carbide populations determining the pre-existing barrier strengths in the superposition of contributions of both the unirradiated and irradiated microstructures to hardening [29,39,60].

(5) The multiple roles of flux and hence the various flux dependences that can and have been observed. For instance:
   a. at high fluxes, UMD's provide increasing hardening with increasing flux, but serve as sinks for point defects thereby reducing the contribution of radiation-enhanced precipitation to hardening [72,76];
   b. at low fluxes, thermal diffusion can predominate leading to an apparent flux (time) dependence [29,31,76];

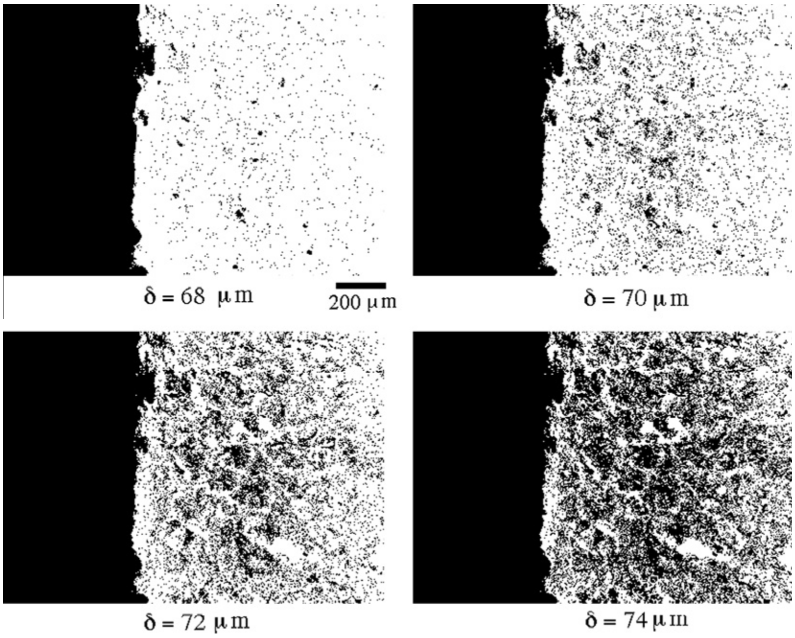

Fig. 8. Example of results from confocal microscopy and fracture reconstruction of a fracture toughness specimen at various levels of crack opening displacement δ. The white regions represent intact material and dark regions represent areas of separation or damage ahead of the blunting crack tip.

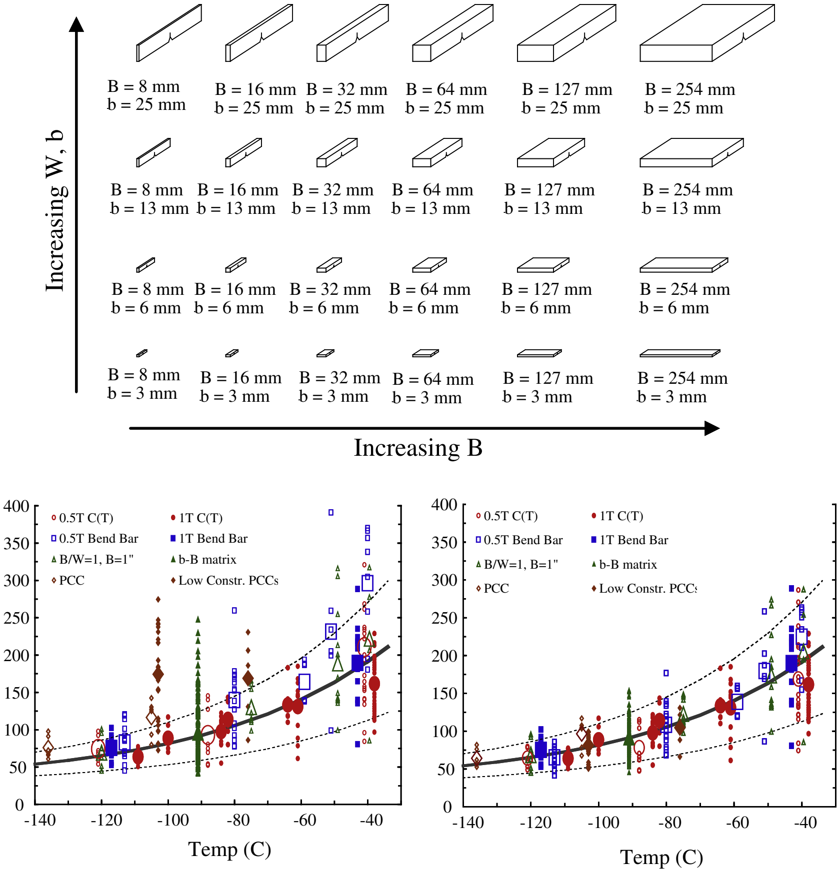

Fig. 9. Illustration of the size effects experimental matrix with systematic variations in *b* and *B*. Measured fracture toughness versus temperature with and without size corrections.

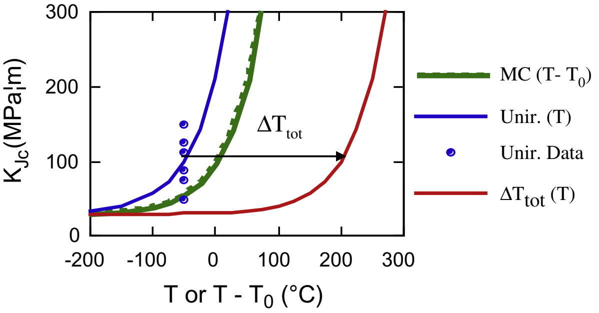

Fig. 10. Illustration of the master curve approach to determining $K_{Jc}(T)$.

Table 1
Students and staff (alphabetical order).

Students	Staff
Matthew Alinger	B.L. Chao
Kurt Edsinger	David Gragg
Jeff Flint	Ming He
Joe Hanson	Doug Klingensmith
Mike Hribenik	Bill Sheckerd
Peter Lombrozo	Takuya Yamamoto
Eric Mader	
Howard Rathbun	
Cindy Sheeks	
Jonathan Smith	
Roger Stoller	
Greg Tedeski	
Brian Wirth	

   c. at intermediate fluxes, where-irradiation-enhanced precipitation predominates hardening and embrittlement, the fluence to achieve a given level of hardening is flux independent, but solute trapping can provide a small degree of flux dependence [77,78].

(6) The role of irradiation temperature in mitigating the defect population evolution and thus hardening and embrittlement. For example:
   a. increasing irradiation temperature reduces the population of UMD's at higher temperatures – leading to reduced hardening at higher temperatures [45,50,72,76];
   b. the contributions of thermal diffusion at higher temperatures can also affect both flux and temperature dependence [45,50];
   c. Mn–Ni rich precipitates are promoted at lower irradiation temperatures [50,74].

(7) The role of various defect populations in both post-irradiation annealing and re-irradiation embrittlement. As noted previously, post–irradiation annealing can lead to the annihilation of UMD's and the dissolution/coarsening of precipitates with increasing time and temperature; re-irradiation embrittlement is then affected by the degree of solute returned to solution during PIA [46–48,79].

This fundamental understanding of the radiation damage evolution and attendant property changes have led to a number of embrittlement correlations that have been used by regulatory agencies to assess the degree of embrittlement of operating RPVs. The understanding and models are used to craft a mathematical framework which is calibrated by multivariable regression analysis on RPV embrittlement data bases, leading to a correlation between transition temperature shift, as measured in Charpy V-notch tests, and intrinsic and extrinsic variables. The approach dates back to early revisions of Regulatory Guide 1.99 [80] to more recent Eason-Odette correlations [81–83]. Moreover, as noted above, a similar approach of combining theory, modeling, and results from large, systematic experimental matrices have been used by Prof. Odette and co-workers to develop correlations for other behavior, including PIA [79,84] and size effects on toughness [65,66,85]. These have all served to assist the industry in evaluating the state of operating RPV's and their service-worthiness under a variety of operating and accident scenarios.

Finally, a long list of students, scholars and researchers have passed through UCSB and had the great privilege of working with and learning from Prof. Odette. Table 1 lists those that have worked in the area of RPV steels, and many are still active in this area today.

5. Summary and conclusions

I have attempted here to provide some appreciation for the unique combination of intellect, insight and ability that Prof. Odette has brought to the community and problem of RPV embrittlement. The combination of his skills in irradiation testing, modeling, and analysis have led to tremendous advances in not only our fundamental understanding of the embrittlement phenomena, but robust correlations that serve the industry well today. He has been perhaps the major contributor to our understanding of RPV embrittlement. His extraordinary contributions to the RPV community are paralleled in fusion materials, composite materials and other material systems. He has leveraged knowledge gained from one area to improving our understanding in the areas. This has truly been a gift to the structural materials community as a whole.

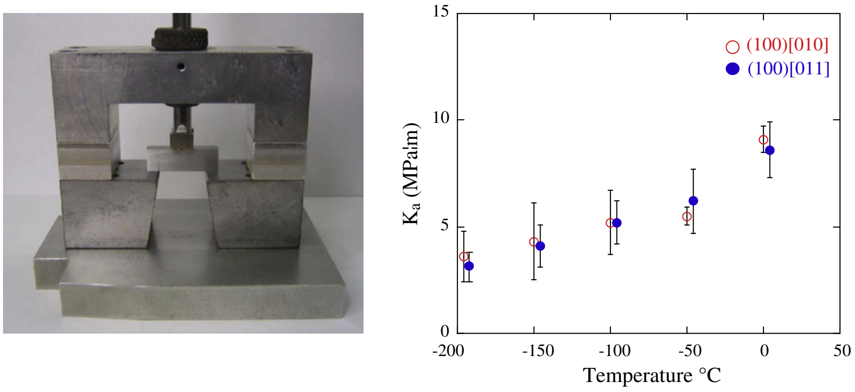

Fig. 11. Illustration of one of the test configurations to determine crack initiation and arrest micro fracture toughness of single crystal iron as a function of temperature, and example results for two crystal orientations.

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