

Overview

This publication contains papers presented at the Specialists' Meeting on Radiation Embrittlement of Nuclear Reactor Pressure Vessel Steels which was held on 26–29 Sept. 1990 at Balatonfüred, Hungary. The meeting, jointly sponsored by ASTM and the International Atomic Energy Agency (IAEA) International Working Group on Plant Life Management, was hosted by the Nuclear Power Plant-PAKS, the Atomic Energy Research Institute (Budapest), and the Hungarian Atomic Energy Commission. The technical content is highly focused on the title subject, which is crucial to the continued operating safety of commercial nuclear electric power generating plants, as it treats the phenomenon of neutron embrittlement of the primary containment vessel of the nuclear reactor power source. Integrity of this nuclear reactor component is a primary goal of all the specialists who have participated in this series of four international meetings. Prior meetings were held in Vienna in 1981 and 1984 and in Philadelphia in 1987. Proceedings are published, respectively, in ASTM Special Technical Publications numbered 819, 909, and 1011.

These international meetings and the publications arising from them offer a progressive series of volumes that provide a valuable technical resource to nuclear power plant operators, national regulatory specialists, and researchers in this area of nuclear safety. The progressive nature of these publications is particularly valuable in teaching scientific and technical developments on what has become one of the most critical elements in reactor safety analysis with the aging of nuclear power reactors. The progress of research and vessel surveillance for neutron embrittlement reflects the aging of nuclear power reactors and, therefore, the attendant interest in assuring safe life attainment for this crucial element of electric power generation, as we approach the close of the Twentieth century. Continuing and even renewed interest in nuclear power is reflected by the growing need for clean electric power and concern for the environment as it is affected by the degradation produced by older fossil-fired power stations.

Traditionally, these joint ASTM-IAEA meetings have sought: international views from a national regulatory perspective, developments derived from continuing assessments of vessel surveillance data, research on the nature and possible means for alleviation of the embrittlement process, as well as the technology for amelioration of embrittlement as it might be applied to a specific nuclear power reactor. As this publication reflects a growing input from Central and Eastern Europe, we encompass in our collective analysis different steels, different reactor types, and thereby, different research and vessel surveillance results. Accordingly, the traditional format has been broadened to include: National Perspectives, Surveillance Programs and Their Results, Fracture Approaches as these apply, Applied and Fundamental Research, and possible means for Amelioration of Radiation Effects which may contribute greatly to plant life management with assured vessel integrity. Thirty-one papers are published from the meeting which attracted seventy specialists from twenty countries. While discussion did follow each paper, it was not recorded. However, a final session was devoted to discussion oriented especially towards the major conclusions of the meeting and what should be done to enhance further the value of future specialists' meetings in this series. This discussion and related conclusions and recommendations are summarized at the close of this Overview.

The session on National Perspectives was intended to draw overviews from national representatives who could and would describe current nuclear power conditions from the

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view of vessel radiation embrittlement as well as regulatory perspectives on national nuclear power research affecting reactor vessel conditions. An apparent sensitivity to publicly projecting these national views limited the descriptions of nuclear power status and the efforts to understand and manage the problem of neutron radiation embrittlement for reactors of the three nations, the former USSR, the United States, and Spain, who presented such general views. These papers were especially useful as a starting point for the more detailed discussion of the following sessions, especially those dealing with surveillance and research studies.

The largest single subject group of papers (ten) dealt with Surveillance Programs and Their Results. Note that a preceding meeting of the IAEA was based on a Coordinated Research Program (CRP) aimed at Optimizing Surveillance Programs and Their Analysis. Most of the national participants of this program were present at the subject meeting and contributed from a base of results on specially developed steels under study in 14 countries with the goal cited in the program title. Thus, the interest was quite high in the Surveillance papers which often form the database for national guides to radiation embrittlement regulatory decisions.

The scope of the Surveillance papers was quite broad with the following areas of emphasis:

- (1) specific results from Central Europe on reactors of Russian design.
- (2) the question of radiation sensitivity as developed from surveillance results in former Yugoslavia and France,
- (3) the development and use of surveillance results by the plant owners.
- (4) development of data for guiding support of life attainment in U.S. reactors,
- (5) use of mechanistic models to guide the analysis of surveillance data,
- (6) development of a "master integrated surveillance program" by a group of reactors from a single manufacturer, and
- (7) applying surveillance dosimetry results for analysis of surveillance data from reactors of a specific design.

One overriding factor of emphasis was the need for assurance of program data validity so that it might be applied to a plants' vessel integrity analysis. This evident need led to the suggestion for an international databasing activity as a followup activity of the IAEA's CRP. This effort would use IAEA resources and background data from the CRP Phase 3 program, the U.S.'s Electric Power Research Institute (EPRI) and Nuclear Regulatory Commission surveillance database, and similar data from other nations. (A proposal has since been developed to initiate such a program, and a favorable decision by those involved seems assured.)

Three papers focused on the critical question of *Fracture Approaches* for radiation embrittlement analysis. These recognized and dealt with the prevalent need to glean the largest possible amount of dynamic fracture data from small specimens and demonstrate their applicability to the large reactor vessel. This statement is not to suggest that only these papers dealt with this need, as most of the papers did in one way or another, since our only hope for projecting vessel integrity from research and surveillance data depends upon the best possible understanding of potential fracture from small specimen data. This critical element continues to receive prime emphasis as a need for added research on irradiated steels and for surveillance program interpretation. The latter statement is one of several conclusions that arose from each of the ongoing specialist meeting series and is also the basis for much of the *Applied Research* which forms the second largest (six) group of papers in this publication.

Despite research on the topic of radiation effects on steels for more than 30 years, Applied and Fundamental Research continues. The six papers in the applied category may be identified as providing results in the following categories:

- (1) embrittlement and the probability of vessel failure, a growing effort throughout nuclear-powered countries for obvious reasons;
- (2) the influence of specimen orientation on the validity of the data to describe large section performance;
- (3) the ever-hoped-for nondestructive approach to providing a quantitative basis for establishing embrittlement during service;
- (4) determination of the embrittlement of specific steels from sources in the United States, Europe, and the former USSR; and
- (5) results of fracture and irradiation results based on the specially selected and tailored steels of the IAEA CRP.

The latter involved a large effort directed at techniques of study, relative sensitivity of various steels, and the role of chemistry on the sensitivity of specially tailored steels. (This study has been described by various investigators and is being included in a special volume now underway by the IAEA on the state of knowledge on vessel steel embrittlement.)

Fundamental Research for the purposes of this publication is essentially that aimed toward understanding the nature and causes of embrittlement by energetic neutrons in steels. With the separation between the Applied and Fundamental Research studies and, to some degree, the Surveillance and Amelioration studies, it is based upon the principal goal of the individual paper and may be somewhat arbitrary. Nevertheless, the three papers designated fundamental research are aimed at (1) understanding the defects produced by neutron irradiation and their interactions, (2) modeling by physical descriptions the nature of embrittlement causing defects introduced by neutron exposure, and (3) the role of preirradiation microstructure and chemical composition upon the postirradiation microstructure and properties of specific reactor vessel steels.

The third largest grouping of papers in this publication is that described under the heading Amelioration of Effects. This is a measure of both the maturation of nuclear power and of those who handle and regulate the operation of these systems. This heading refers to the number of studies of irradiation and the means for correcting the embrittlement by postirradiation heat treatment or annealing at temperatures above those of operation as well as those studies that cite other actions to optimize vessel life. Papers in other sections, especially Surveillance and Applied Research, also have been aimed toward this latter goal. Of course, both annealing and other operational actions are responses to the need to assure vessel integrity as they age and are exposed to progressively greater neutron exposure levels. This is the primary basis for listing this group of six papers at the end of this volume. This series offers alternatives which may provide confidence on the part of operators and regulators that continued safe operation can be attained for a known lifetime.

At the meeting's final session, certain collective conclusions were sought through open discussion among principals and then among all participants. These conclusions covered both technical results and guidance for future activities to meet goals of this series of ASTM-IAEA meetings.

Technical conclusions were logically general in nature and are cited. There was no opportunity for detailed consensus conclusions, but those listed do indicate the directions agreed upon and to note discrepancies. Generally, surveillance and research results showed the vessels to be in better condition than would have been predicted by the

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primary regulatory trend curves used of the U.S. Nuclear Regulatory Commission and those of approximate equivalence in the former USSR. However, at least two papers concerning reactors in the eastern part of Germany cited sufficient embrittlement to require annealing of the vessel. (Since the meeting, a reactor in the United States and one in Germany have been shutdown pending full safety review before further operation.)

Some related additional conclusions are provided:

- (1) U.S. reactor owners have organized groups to collect and analyze surveillance data comparing especially results from similar reactors;
- (2) surveillance results from similar reactors at the same or different sites are established as broader integrated surveillance programs of direct interest to several owners;
- (3) there is clearly a strong need for a systematic gathering of data from vessel surveillance in a database similar to but more extensive than that within the IAEA's Coordinated Research Program, Phase 3;
- (4) older plants use surveillance data to help demonstrate the validity of plans for life attainment and even life extension; and
- (5) results from newer plants show the benefits of improved steels which show smaller changes than those predicted in regulatory trends.

More than one third of the papers dealt with the subjects cited above thereby indicating the importance attached to them.

In seeking more specific conclusions, the next most frequently heard topic was research based on steels in the reactors of Central and Eastern Europe. Such topics were discussed as positron annihilation to determine the physical nature of neutron damage; the critical chemical component elements in causing embrittlement; the influence of impurity or alloying elements, especially those of copper, phosphorus, nickel, and vanadium; the potential for annealing to correct embrittlement; and even the probabilities of vessel failure under certain circumstances. Some conclusions and some differences of opinion follow:

- (1) because of the fact that phosphorus has a significant influence on irradiation embrittlement there was disagreement on the level and nature of its role and any synergistic influence with copper;
- (2) the relative roles of nickel and vanadium were also discussed without agreement, though in the vanadium-containing Russian steels, vanadium was shown to affect the level of embrittlement (the possible synergism of nickel and vanadium with copper was cited as an uncertainty);
- (3) the use of fracture mechanics specimens in research and surveillance was the source of much discussion with an agreed need for standardization and correlation with the widely used standardized Charpy results;
- (4) it was generally agreed that more fundamental studies are needed to clarify further the physical mechanisms of embrittlement;
- (5) the issue of the existence of a flux or irradiation rate effect was cited by several authors as needing clarification; and
- (6) the role of microstructure, even the definition of microstructure, was discussed along with evidence of significant effects that have been dismissed in the past by some investigators.

At the end of the meeting, general discussion led to certain recommendations. Before specific recommendations were gleaned, however, it was agreed that for several reasons

this was by far the most successful of the four meetings in this series held triennially since 1981 and that the series should be continued. Some of the reasons for this success that should be considered in planning the future followup meeting were cited. These reasons were the interaction, for the first time, of large numbers of individuals from Central and Eastern Europe along with those of other "nuclear" countries from the West; agreement of the overwhelming negative influence of a nuclear accident no matter where it may occur in the world; the related great and continuing need to assure the structural integrity of the primary pressure vessel to assure nuclear system safety; as well as the aging of nuclear plants in many nations at a time of great demand for added sources of electricity.

Based on this agreed background, the success of this meeting was acclaimed and the question was raised as to its future. From this discussion grew several recommendations predominately procedural in nature.

The recommendations listed were adopted by acclamation:

1. The current emphasis and focus on the pressure vessel and its embrittlement by neutron radiation must continue.
2. Retain the international nature of this meeting.
3. Consider seriously reducing the time period between meetings from three to two years.
4. Encourage papers that help to resolve questions raised in the conclusions, especially better data analysis from surveillance programs, better knowledge of the causes of radiation embrittlement (fundamental and applied research), and special attention to annealing as a means to correct damage.
5. Enforce IAEA guidelines on the number of participants and structure of the meeting to assure adequate time for discussion.
6. Consider inclusion of a specialized workshop within the meeting framework which allows a dedicated emphasis on a "theme" topic of serious concern to reactor owners-operators.
7. Continue the collaboration with ASTM to assure a continuing series of progressive hardbound volumes which form a historical structure of results in this focal topic.

In closing, I especially wish to acknowledge those who supported the meeting and this publication. There are too many to name, but those who made it a success were the authors, organizers, discussers, and the host of reviewers (more than 90). Specific recognition and personal gratitude go to the principal organizers, Ferenc Gillemot and his Hungarian Committee and Leonid Ianko, Scientific Secretary from the IAEA, as well as our hosts, Director Ponya and other officers of the PAKS nuclear power plant. Those in the Hungarian Organizing Committee besides Dr. Gillemot of the Atomic Energy Research Institute were Dr. P. Trampus from NPP-PAKS and Ms. E. Urban of the Hungarian Atomic Energy Commission. For support of this publication I am grateful for the ASTM staff especially Monica Siperko, Rita Hippensteel, Kathy Dernoga, and a group of talented editors. Also deserving of special recognition were the reviewers (three per paper) who worked so diligently and anonymously to assure a correct and valuable publication. To all of you I hereby express heartfelt thanks. This is your volume, not mine.

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