UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

DEC 28 1979

MEMORANDUM FOR: Harold R. Denton, Director
Office of Nuclear Reactor Regulation

Robert B. Minogue, Director
Office of Standards Development

FROM: Saul Levine, Director
Office of Nuclear Regulatory Research

SUBJECT: RESEARCH INFORMATION LETTER # 76 - ANNEALING OF IRRADIATED REACTOR PRESSURE VESSEL

Introduction and Background

This research information letter summarizes the information developed over the past 15 years on the use of post-irradiation heat treatment (annealing) to recover the preirradiation properties of reactor vessels of commercial nuclear power plants for continued safe operation. The information is to be viewed as providing a background for interpreting current and future research activities and potential licensing applications of vessel steel annealing.

A progressive reduction in the fracture toughness of low alloy steels typically is produced by the radiation service conditions of LWR pressure vessels. This reduction is typically measured by a decrease in Charpy-V (C_V) upper shelf energy level and by an elevation in the ductile-to-brittle transition temperature of the steel. The ASME Boiler and Pressure Vessel Code (Section III) and the Code of Federal Regulations (10CFR50) both recognize this degradation in fracture toughness by irradiation. Limitations are imposed on post-irradiation properties for fracture-safe reliability and the vessel steels are monitored by surveillance programs. One requirement has been the maintenance of 68J (50 ft-lb) C_V as a minimum toughness level to preclude the necessity for a detailed fracture mechanics analysis.

At present, there is little doubt that Code fracture toughness requirements over projected service lifetimes can be met by recently constructed reactor vessels having carefully controlled steel chemistry. A concern does exist, on the other hand, for a large number of reactor vessels fabricated prior to 1971. Here a combination of factors, including high copper and phosphorus impurities contents and low initial C_V upper shelf energy levels, may exist for the steels and welds which could bar meeting Code criteria after some period of vessel operation. In other words, high copper and phosphorus levels in steel plates and weld deposits have been correlated with a high sensitivity to radiation embrittlement. A low upper shelf energy before irradiation compounds the problem by providing less of a margin for detrimental radiation effects.

Post-irradiation heat treatment (annealing) is one of two options open for extending vessel life if fracture toughness properties are reduced to levels below Code requirements. The potential of this method for the reversal of radiation effects, i.e., fracture toughness recovery, was revealed by studies at the Naval Research Laboratory (NRL) as early as 1960 and a precedent for use of the method has been established with the successful in-place anneal of the SM-1A reactor vessel by the U.S. Army with guidance from NRL. The second option offered by 10CFR50 involves an essentially complete volumetric examination of the beltline region of the vessel and the subsequent fracture mechanics analysis which "conservatively demonstrates, making appropriate allowances for all uncertainties, the existence of adequate margins of safety for continued (sic, vessel) operations." This latter option assumes that Charpy-V energy absorption could be allowed to go below 68J (50 ft-lb) in select cases. Because of the indicated promise of the heat treatment (first) option, RES has sponsored research at NRL to assess the potential of this method for embrittlement relief of commercial reactors.

Research Progress

A recent NRL study has analyzed the factors which may influence steel response to post-irradiation heat treatment. The study also evaluated currently available data to qualify the suspected influences on steel recovery. For the latter, NRL compiled and reviewed experimental results generated over the past 15 years on commercial production vessel steels and companion steels produced in the laboratory. The study and its interpretations have been published in the enclosed NUREG/CR-0486. The data compilation included in the report is the first of its kind.

To summarize its most important conclusions, the study revealed that twelve metallurgical and service variables may influence post-irradiation heat treatment behavior; at least six are shown to have an influence on fracture toughness recovery. The large number of operating variables thus makes the projection of fracture toughness recovery for specific vessel conditions complex. Fortunately, the data generated to date indicate that annealing temperature and duration have the greatest influence on recovery. Annealing at a temperature of 400°C (750°F) or above, for as little as 1 week, offers significant promise for reactor vessel embrittlement relief particularly if annealing is started early in life. For example, transition temperature recoveries between 55 percent and 75 percent were found for most materials with this heat treatment. More important to older vessels, full upper shelf recovery for fluences up to $3 \times 10^{19} > 1$ MeV appeared typical for the materials of concern. On the other hand, it is concluded that annealing at a lower temperature, 343°C (650°F), which does not require removal of the core, does not appear to offer a similar benefit once the fluence has exceeded 1×10^{19}; insufficient data exist to define the benefits of this low temperature annealing for fluences less than the preceding.

Overall, the study has enhanced the potential of the annealing method as one means of coping with unacceptable radiation effects should the need arise.

Evaluation and Applicability

Although major progress has been made, the present state-of-the-art is insufficiently advanced to permit an immediate application of the annealing method for relieving reactor vessel embrittlement. The most important reason for this is that experimental data describing subsequent fracture toughness degradation with reirradiation, following the initial irradiation and annealing, are too sparse to confidently base engineering judgments and property projections for this condition. Beyond the first cycle of annealing and reirradiation, information on notch ductility and fracture toughness trends after multiple annealing and reirradition cycles is quite limited. Equally important, knowledge of the factors governing reirradiation behavior (i.e., sensitivity of the steel and reirradiation rate) is also limited. This issue is very important since NRL has established that the rate of reembrittlement of annealed material is significantly greater than that of nonannealed material at an equivalent fluence level. Moreover, the trend in upper shelf reduction with reirradiation appears to be significantly different from that of nonannealed material. Thus, while high temperature annealing shows great promise for embrittlement relief, additional research must precede its application.

Future Work

RES continues to coordinate NRL's research on annealing with NRR and SD personnel. The current phase of the NRL work is awaiting the recommendations from Task Action Plan A-11, Reactor Vessel Materials Toughness, on fracture toughness requirements of irradiated vessel materials that could require annealing.

In its annealing research, NRL is using either archive samples of low ductile shelf materials from power plants currently in operation, or duplicate materials fabricated to the same specifications. Future research on multiple irradiation and annealing should emphasize heat treatment at the higher temperature of 400°C (750°F) and treat the fluence at initial annealing and subsequent irradiations as a major variable. This is advisable because many older reactor vessels may have already exceeded the fluence level at which multiple annealing could ensure a continuing low level of embrittlement. Furthermore, a series of tests must be performed to determine if the reembrittlement, after annealing to the level that existed before annealing, occurs rapidly or gradually.

RES maintains close liaison with the annealing work underway at EPRI and in the Federal Republic of Germany. While the NRL work is examining trends and mechanisms, the EPRI work is concentrating on systems considerations. The FRG work addresses both trends and systems considerations, but employs "worst case" lower-bound materials and conditions. All information obtained from other sources will be factored into the NRL work and forwarded to NRR and SD, as they become available, for consideration in future applications of annealing to fracture toughness recovery of reactor vessels.

Technical questions concerning these results may be referred to Mr. Charles Z. Serpan, Chief, Metallurgy and Materials Research Branch.

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Office of Nuclear Regulatory Research

Enclosure: NUREG/CR-0486,
NRL Report 8287, "Survey of Post-irradiation Heat Treatment as a Means to Mitigate Radiation Embrittlement of Reactor Vessel Steels," J. R. Hawthorne, Naval Research Laboratory, Washington, DC, February 1979

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