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NEUTRON IRRADIATION EMBRITTLEMENT MODELING IN RPV STEELS - AN OVERVIEW

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Abstract

The degradation of reactor pressure vessel (RPV) steels due to neutron irradiation embrittlement is of particular concern because of its relevance to plant safety and limitation of plant life. In order to ensure structural integrity and safe operation of the nuclear power plant (NPP), it is essential to understand the damage mechanisms in RPV steels and their effect on mechanical behavior of material. To account for the synergistic effects of various embrittlement variables, both microscale and atomic scale models are being successfully used for assessment of structural integrity of RPV. This paper encompasses a brief description of microstructural effects of irradiation in RPV steels resulting in ductile to brittle transition temperature (DBTT) and reduction of fracture toughness, followed by an overview of the existing damage mechanism models. Besides a brief description of the fracture mechanics concept to the irradiation embrittlement, salient features of major damage mechanism models along with the future scope of further developments have been discussed.

***Keywords*:** Reactor pressure vessel (RPV), Neutron irradiation, Embrittlement, Fracture toughness, Damage mechanism model.

1. Introduction

Integrity of the Reactor Pressure Vessel (RPV) is vital to the safe operation of a nuclear reactor. It is therefore essential to monitor and predict the changes in pressure vessel material during operation. Degrading effects of neutron irradiation on carbon and low-alloy pressure vessel steels have been recognized and investigated since the time they were put in operation [1]. In these steels at operating temperatures (around 300°C), radiation damage is produced when neutrons of sufficient energy displace atoms from their lattice sites. Defects formed in the steels as a result of displacements of atoms typically cause hardening and a decrease in toughness. The decrease in toughness is most commonly represented by an increase in the ductile-brittle transition temperature (DBTT) as shown in the schematic Fig.1. This shift in DBTT, which is necessarily associated with reduction in Upper Shelf Energy (USE), is either measured by Charpy-V notch (CVN) impact or fracture toughness tests and a decrease of the upper-shelf energy as measured by the CVN impact test [1]. This paper is intended to presents an overview of basic neutron irradiation damage mechanisms in RPV steels with a description of most commonly used damage mechanism models.

1.1 Background

Nuclear reactors are being used, mainly for power generation, in many countries of the world for over half a century. The core of nuclear reactor is housed in Reactor Pressure Vessel (RPV), hence the life and safety of reactor depends on life and safety of RPV. The RPV is designed and operated in such a manner that its structural integrity has to be maintained so it should not fail in service. The factors which could affect RPV failure rates include the initial quality of the vessel, operating conditions and degradation of the material properties due to service exposure. RPV steel degradation can be caused in a number of mechanisms which includes irradiation embrittlement, thermal ageing, temper embrittlement, fatigue and corrosion. However, Neutron irradiation is the primary mechanism responsible for degradation of the mechanical properties of RPV steels [2].

In the fuel of nuclear reactors, neutrons with energies greater than 0.1MeV, called fast neutrons, and high energy gamma rays are produced. These energetic particles collide with and displace atoms of the structural metals in and around the reactor core [3,4]. The subsequent behavior of displaced atoms is the source of a wide variety of macroscopic effects [5]:

1. Mechanical properties are altered; Metal is hardened, meaning that its yield strength is increased, and fracture toughness is reduced. Both these effects cause “embrittlement” of the alloy which persists even when the irradiation ceases. Creep, the slow distortion of the structure under stress, is also increased while the structure is being irradiated.
2. Irradiation also causes dimensional changes; creation of voids in the metal causes swelling. If the crystal structure is anisotropic, irradiation can also cause growth of the component in one direction.
3. Microscopic properties of the metal are also altered due to irradiation; diffusion of all constituents of the alloy is increased. Irradiation can either destroy precipitates in an alloy or cause precipitates to form. Irradiation can also create new dislocations and may facilitate movement of dislocations.

1.2 Typical RPV steels

RPV steels have relatively high strength and good toughness in the as-fabricated condition. Typical base metals (BM) used in European and American RPVs are A302B, A533B plates, or A508 forgings which are quenched and tempered, and low-alloy steels with primarily tempered bainitic microstructures. However, the Russian RPV metals are slightly different than these. Compositions of main alloying elements in the RPV steels are given in Table1.

Multiple-layer submerged arc welds, made of consumable metal wires, join vessel sections. Compositions of weld metals (WM) differ from the BM, and may vary significantly even within the same weld. Following welding, vessels are tempered and stress relieved, typically at about 620±15°C for about 30 hour, resulting in as-fabricated yield stress values of about 475±50 MPa [6]. Compositions and microstructures of WM vary on both the macro- and micro-scales. Along with Ni alloying additions, trace impurity Cu and P increase embrittlement. Cu contents are quite high (up to 0.4%) in some early welds [6].

1.3 Embrittlement variables in RPV steels

The embrittlement of RPV steels during its service life depends on material chemistry of the steel itself and the irradiation environment (neutron dose) to which it is exposed. Both these parameters are called embrittlement variables. In order to understand and predict the mechanical behavior of RPV steels it is essential to determine the nature of these variables and their synergistic effect. The key embrittlement variables are:

1. Chemical composition of steel, mainly the weight percent of alloying elements and impurities like Cu, Ni, Mn and P.
2. Flux (Φ), the amount of radiant energy(number of neutrons per second) passing through a unit area.
3. Fluence (Φ_t), the number of particles delivered per unit area.
4. Irradiation temperature (T_i).

Out of the above four variables, except the chemical composition, all others are not uniform within a vessel itself and also experience a wide range of variation throughout the service life of RPV. It is therefore essential to model the embrittlement mechanism in an RPV considering the synergistic effects of all these variables.

1.4 Contribution of recently developed techniques in understanding damage mechanisms

A number of recently developed techniques have significantly contributed towards improved knowledge of RPV radiation damage:

1. Developments in experimental techniques for detection of radiation damage in nano-scale features have enabled researchers to know the mechanisms and effects of embrittlement in greater details. Atom Probe (AP), 3D-AP, Positron Annihilation (PA), Small Angle Neutron Scattering (SANS), Field Emission Gun Scanning Transmission Electron Microscopy (FEGSTEM) etc are now being commonly used to study the neutron irradiation in RPV steels [7,8,9,10,11].
2. Modeling of radiation damage processes by computations in atom scale crystal models has been quite useful in understanding damage mechanisms and irradiation effects, as recently demonstrated by Wirth et al [12].

3. Recently a direct method for determining the fracture toughness, named Master Curve (MC), was developed and is receiving wide applicability to RPV steels [13,14,15].
4. Fracture mechanics application to small size specimens is another important development for the surveillance of in service RPV for which more number of tests can now be carried out with small size of specimens [16].
5. Creation of large databases (results from surveillance specimen tests) and their analysis. Networks like ATHENA, AMES, NESC, ENIQ etc and Joint Research Centre (JRC) of European Commission are effectively using the shared data bases for study of degradation effects in various types of RPV steels [17].

2. Microstructural effects of irradiation in RPV steels

The specific changes in microstructure of the RPV steel as a result of exposure to irradiation are as follows:

1. Formation of lattice defects [3,4].
2. Phase transformation accompanied by formation of various precipitates population [18].
3. Formation of impurity-vacancy cluster {3,4}.
4. Segregation of phosphorus and may be some other impurities at grain boundary [18].
5. Impurity segregation at interfaces between secondary phases and matrix and/or radiation defects [18].

The above radiation induced structural changes may induce complex, synergistic changes in steel behavior which can not be explained with the use of a single mechanism.

3. Irradiation embrittlement in RPV steels

The primary mechanism of embrittlement in RPV steels is the hardening produced by nanometer features that develops as a consequence of irradiation. The key embrittlement processes, as illustrated in flow diagram of Fig. 2, include [19]:

1. Generation of lattice defects in displacement cascades by high-energy recoil atoms from neutron scattering and reactions. The primary defects are in the form of single and small clusters of vacancies and self-interstitials.
2. Diffusion of primary defects also leading to enhanced solute diffusion and formation of nanoscale defect-solute cluster complexes, solute clusters, and distinct phases, primarily copper-rich precipitates (CRPs).
3. Dislocation pinning and hardening by these nanofeatures.
4. Hardening-induced DBTT shift (ΔT).

The three basic micromechanisms of irradiation embrittlement, identified and agreed world-wide to control embrittlement in RPV steel [20,21] are:

1. Irradiation enhanced formation of copper-rich precipitates;
2. Matrix damage due to radiation produced point defect clusters and dislocation loops;
3. Irradiation induced/enhanced grain boundary segregation of embrittling elements such as Phosphorus.

The first two of the above mechanisms serve to harden the material and increase the yield strength σ_y, whilst the third mechanism causes a drop in the fracture strength, σ_F [22].

The irradiation induced DBTT shift (ΔT) is governed by three factors summarized by the following equation [23,24]:

$$\Delta T = B + A_m F_T \sqrt{D} + C(D-D_0)^n \tag{1}$$

In this equation, the first term B relates to an increment in yield stress due to Cu precipitate-hardening; the second term $A_m F_T \sqrt{D}$ represents the effect of “matrix damage” resulting from increase in yield stress due to point-defect or cluster hardening (where Am is the “matrix sensitivity to damage”, F_T is a temperature-dependent factor and D is the irradiation dose (dpa)); the third term $C(D-D_0)^n$ relates to the decrease in (local) fracture strength as a result of the segregation of P to grain boundaries (where C and n are constants, to be determined experimentally, and D_0 is a threshold dose, below which segregation does not affect the fracture strength).

Main embrittlement processes are closely connected with two types of RPVs – PWR/ BWR and WWER with their different material types and historically also connecting different type of detrimental elements – mostly Cu in PWR/ BWR and P in WWER [17,18].

In the case of PWR/BWR RPVs the dominant features in highly embrittled steels are Cu-rich precipitates (CRPs) or Cu-catalyzed and Mn-Ni-rich precipitates (MNPs) [6,17,18,]. Additionally, two types of matrix defects evolve: those that are thermally unstable (UMDs) and those that are stable at typical RPV operating temperatures (SMDs) [6]. UMD, although thermally unstable at the irradiation temperature, are frozen into the microstructure during the cool-down after irradiation.

In the case of WWER RPVs Cu is usually less important as main damage is connected with P due to its high content in steel. Its damaging effect is either in segregation on grain boundaries with subsequent intergranular fractures or precipitates with other solute atoms inside grains [6,17,18]. This second model is now more widely accepted as it can explain also RPV material behavior during annealing and further re-embrittlement. However, effect of Cu is still leading in most of the studies while more detailed studies of Phosphorus effect have started only several years ago.

Exposure to irradiation (or elevated temperatures) also causes the segregation of phosphorus to internal grain boundaries in RPV steels. This, in turn, encourages brittle intergranular failure of the material. In Europe a project named PISA has been initiated to specifically address the effect of Phosphorus segregation in RPV steels [25]. PISA (Phosphorus Influence on Steel Ageing) is an AMES (Ageing Materials European Strategy) related project of Joint Research Centre (JRC) under European Commission (EC), with the objectives to improve predictability of a failure mechanism that can affect all types of reactor plant operating in Europe, and in particular to improve the predictability of mechanical property changes in long-service steels for plant applications.

In “high-nickel” RPV steels different problem are also found. Models and increasing experimental evidence suggest that phases rich in Ni and Mn may form in low Cu steels [26]. Results of thermodynamic calculations show Mn-Ni rich precipitates are promoted by increasing Ni and Mn content and lower irradiation temperatures [17]. Since these phases may require a small degree of Cu precipitation to catalyze their nucleation, they may not contribute to hardening and embrittlement until relatively high fluences. The delayed embrittlement caused by these so called “late-blooming phases” could produce an effect that could have serious implications to RPV life extension [6,17].

4. Fracture mechanics applications to irradiation embrittlement in RPV steels

The fracture toughness of a material is considered a direct measure of degradation in mechanical behavior of RPV steels. In order to monitor and predict the integrity of RPV, the fracture toughness of RPV steels is measured through surveillance programs [6]. RPV integrity assessments require evaluations of sharp crack, mode I fracture toughness-temperature curves for static $K_{Jc}(T)$, dynamic $K_{Id}(T)$ and arrest $K_{Ia}(T)$ loading conditions in the cleavage transition regime, as well J-R based measures of ductile initiation and tearing resistance toughness.

Over the past few decades, developments in Elastic-Plastic Fracture Mechanics (EPFM) have been largely driven by the need for accurate prediction of irradiated RPV behavior a number of consensus standards and codes (ASME, KTA, RCC-M, MITI and Russian Codes) have already been developed for determining K_{Ic}, K_{Ia}, K_{Id} ,J_{Ic} and J-R curves as a function of temperature normalized to a reference nil ductility temperature, RT_{NDT} [27]. These standards have led to a consistent determination of those properties that in turn have resulted in the development of databases that are useful for statistical analysis and establishment of uncertainties.

One of the accepted methodologies to determine the irradiation induced DBTT shift in RPV steels is to experimentally determine the shift in the 41J Charpy energy level index temperature ΔT_{41}, which is assumed to produce an equal shift in the RT_{NDT} of the material [28]. The relationship of Charpy index and NDT to fracture toughness fracture behavior of RPV steels has been summarized as follows [29]:

1. NDT is the index against which other fracture parameters are measured.
2. NDT can be characterized by a Charpy energy level index, and for RPV steels this is considered to be T_{41}, the temperature corresponding to an absorbed energy of 41J.
3. The dynamic fracture toughness curve is ostensibly invariant with respect to the NDT.
4. The static fracture toughness curve is displaced to a lower temperature than the dynamic curve, and the extent of the displacement is inversely dependent on yield strength.

The schematic representation of the above points with reference to a usual toughness index of 100 MPa$\sqrt{m}$ has been shown in Fig. 3 [29].

Major irradiation projects have provided critical information regarding the fracture behavior of RPV steels under conditions of irradiation, thermal annealing, and re-irradiation, to include the effects of Cu and Ni content, the relationships between Charpy-impact toughness and fracture toughness/crack-arrest toughness, stainless steel cladding, and low upper-shelf welds [17]. It is also established through experiments of project FRAME that generally, shifts in transition temperatures of CVN and static fracture toughness tests seem to be roughly equivalent which simplify RPV integrity assessments [17,30]. FRAME (Fracture Mechanics Based Embrittlement Trend Curves for the Characterization of Nuclear Pressure Vessel Materials) is another AMES related project, it aimed at development of a master curve approach for irradiated materials, giving for the range of investigated materials additional valuable information and replacing present correlation methods by direct measurement of fracture toughness [25].

5. Damage mechanism modeling

As stated above, the complex synergistic changes in steel behavior caused by neutron irradiation, as a function of embrittlement variables, can not be explained with the use of a single mechanism because there exists no unified exact method of deriving models in the field of materials science due to presence of a large variety of scales and mechanisms [31]. Therefore, a number of damage mechanism models have been introduced to understand the behavior of RPV steels. Some of the important damage mechanism models are briefly discussed below:

5.1 Prediction models

The mechanistic understanding of irradiation embrittlement in RPV steels has lead to formulating robust, physically based and statistically calibrated models of CVN-indexed transition-temperature shifts [18]. These semi-empirical models account for key embrittlement variables and variable interactions, including the effects of material chemistry (Cu, Ni, and P) and environment i.e. Fluence (Φ_t), Flux (Φ), and irradiation temperature (T_i) [32,33].

Models of evolution of nano-scale precipitates rich in Cu, Mn, and Ni have been found quantitatively consistent with experimental observations of the complex interplay between these elements and other embrittlement variables [34]. These models also explain other effects, such as those associated with post-weld heat treatment and many aspects of the interactive flux-composition-temperature dependence of embrittlement [35].

The most commonly used model to predict brittle fracture in RPV steels is Beremin's Probabilistic Model [36]. According to this model the brittle fracture probability P_f of a cracked specimen is calculated for stress intensity factor $P_f(K_I)$ or J-integral $P_f(J)$ [37]. The brittle fracture probability of a cracked specimen according to Beremin's model is written in the following form:

$$P_f = 1 - \exp[-(\sigma_w / \sigma_d)^{\eta}] \qquad (2)$$

In the above equation σ_w is the Weibull stress; σ_d and η are the temperature independent Weibull parameters. In probabilistic model, the curve $K_{IC}(T)$ as shown in schematic Fig. 4 is used to estimate the fracture toughness of the material.

The Master Curve approach developed by Wallin [38,39,40] is another widely used method for prediction of the temperature dependence of fracture toughness for RPV steels. The master curve describes the temperature dependence of the J-integral related fracture toughness, K_{Jc}, on the base of a statistical brittle fracture model und using a reference temperature, T_0, for temperature scaling.

The procedure of the determination of T_0 has already been established in the international standard regulation [41,42]. This approach allows the prediction of the $K_{IC}(T)$ curve for any given fracture probability and any specimen thickness on the basis of small-sized specimen testing. Master Curve approach for RPV steels provides adequate predictions for materials in the initial state and for cases when the degree of embrittlement is not high. However, for high degrees of embrittlement, the Master Curve may provide inadequate and non-conservative predictions [43,44].

Master Curve application, initially developed for western RPVs, is now permitted for RPV integrity/lifetime evaluation by ASME Code Cases as well as for WWER RPVs by VERLIFE Procedure [45]. VERLIFE was a project launched to create a "unified procedure for lifetime assessment of components and piping in WWER type nuclear power plants" [46].

The prediction models of primary irradiation embrittlement have also been extended to treat post irradiation annealing (PIA) and re-embrittlement (RE) based on tracking the fate of key alloy constituents and defects {47}.

5.2 Physical modeling

The physical basis underlying the models is mainly the evolution of precipitates (Cu, Mn, Ni, P etc) and the grain boundary segregation of impurities in RPV steels during irradiation as stated above. Since this evolution and the nature of the features are linked to the key embrittlement variables and how they mediate embrittlement through the micromechanics of the transition temperature shift, it is therefore that the construction of physical models is considered helpful in understanding the embrittlement mechanism.

The matrix defects; those that are, at high fluxes, thermally unstable (UMDs) and those that are stable at typical RPV operating temperatures (SMDs), are the features that evolve primarily as a consequence of radiation-enhanced diffusion and defect clustering, and their evolution can be modeled in terms of these processes [6,17]. It may be noted that at present, no microstructural technique has the capability to identify all irradiation-induced microstructural features. However, the combination of FEGSTEM, OPoSAP (3D-AP) and SANS provides complementary data on both precipitation and matrix chemistry [48].

Commercially available modeling software like ABAQUS and ANSYS are being used to physically model the irradiation induced defects in the structure of specific RPV for assessment of its structural integrity [49]. At a larger scale of physical modeling, project PERFECT is initiated in Europe to develop multi-scale numerical tools, modeling and simulation of irradiation damage on reactor nuclear components using an integrated and problem oriented approach [50]. Prediction of Irradiation Damage Effects on Reactor Components (PERFECT) is a project of the current European Framework Program FP-6.

5.3 Computational modeling

The computational advances in the late 20th and early 21st Centuries have paved way to a new emerging field of Computational Materials Science (CMS) [31]. Recent years also have witnessed rapid advances in computational capabilities for realistic simulation of complex physical phenomena such as irradiation embrittlement. Through very close integration with experiment, and incorporating advances in the underlying scientific understanding in pertinent areas of materials science and mechanics, the potential of realistic simulations of the long-term in-service performance of reactor components has become a reality.

The typical examples of atomistic models are classical Molecular Dynamics (MD) and Kinetic Monte Carlo (KMC) methods [28]. Classical MD is a powerful method for obtaining insight about the dynamics of physical processes that occur on relatively short time scales. Current computational capability allows treatment of atomic systems containing as many as 10^9 atoms for times on the order of 100 nano-seconds. MD simulation is an ideal technique for studying the evolution of displacement cascades, as a result of the short temporal evolution. Large vacancy and self-interstitial clusters are produced within a few tens of picoseconds as the kinetic energy is dissipated and the cascade cools. In MD simulations, the large vacancy clusters have been found to collapse to form stacking fault tetrahedra (SFT) within a few picoseconds at room temperature [51]. The formation of large point defect clusters in high-energy displacement cascades is one example of the improved understanding of radiation damage that has resulted from atomistic simulations.

In KMC modeling of radiation damage, the location and fate of all defects, impurities and solutes is tracked as a function of time to predict microstructural evolution. The starting point in these simulations is the primary damage state, i.e. the spatially correlated locations of vacancy and interstitials produced in displacement cascades resulting from irradiation and obtained from MD simulations, along with the displacement or damage rate which sets the time scale for defect introduction. The defects execute random displacements of diffusion in one or more dimensions, depending on the nature of the defect, with a probability (rate) proportional to their diffusivity. Similarly, cluster dissociation rates are governed by a dissociation probability that is proportional to the binding energy of a particle to the cluster. The basic steps in a KMC simulation are summarized by Wirth et al [51].

The main limitation of classical MD simulation is the relatively short times accessible [51]. KMC provides the ability to reach macroscopic times by modeling diffusional processes and time-scales rather than individual atomic vibrations. It involves sampling from appropriate probability distributions to simulate many possible combinations of flaw geometry and RPV material embrittlement subjected to transient loading conditions. Over a period of time, coupling of MD and KMC has developed into a powerful, multiscale tool for the simulation of radiation damage in metals [51].

In Europe a comprehensive simulation of the RPV is being developed under REVE [52]. Reactor for virtual experiments (REVE) is a coordinated international project between USA, Japan and EU to develop tools for numerical simulation of irradiation effects and aging in RPV components in the form of a Virtual Test Reactor (VTR).This application has been considered important in light of the extensive use of existing knowledge base on pertinent damage mechanisms in computational modeling [53]. The first VTR developed under this project, named RPV-1, is capable of simulating irradiation effects in RPV steels of Light Water Reactors. Its input/output parameters are the same as those of experimental programs on irradiation like neutron spectrum, temperature etc and subsequent tensile testing of irradiated materials [50].

6. Discussion and conclusion

In nuclear power reactors, materials of the pressure vessel and its internal components undergo degradation due to severe irradiation conditions. So far, the material databases needed to allow for these degradations in the design and safe operation of installations have mainly relied on long-term irradiation programs in test reactors as well as on mechanical or corrosion testing in specialized hot cells. This predominantly empirical approach is now being complemented and improved, with the help of continuous progress in experimental techniques as well as computer technology, by multiscale modeling of radiation damage mechanisms. These models are capable of simulating the effects of irradiation on mechanical behavior of the materials at a greater level of accuracy.

Though considerably large achievements have already been made in application of results from the research into RPV integrity operation and evaluation, still a lot of work is required to achieve a higher degree of satisfaction in terms of safety evaluation and improved design of RPV's.

The synergistic effects of neutron fluence, flux, and spectrum, the irradiation temperature, and the chemical composition and microstructure of the steel must be understood in greater details to reduce the uncertainties associated with the development of predictive models of embrittlement.
The surveillance databases provide the basis for developing embrittlement correlations as well as for validation of microstructure-based embrittlement models, its characterization for specific type of steels would enable more realistic evaluation of RPV life.

The Master Curve is identified worldwide as a recommended subject for continued research. The issues most identified are the shape of the Master Curve at high levels of embrittlement and at high fluence, specimen size (application to pre-cracked Charpy), dynamic loading (including crack-arrest), the effects of intergranular fracture, and the technical underpinning for the universal shape of the curve [30,54].

Development of Master Curve at high levels of embrittlement and at high fluence, specimen size (application to pre-cracked Charpy), dynamic loading (including crack-arrest), the effects of intergranular fracture, and the technical underpinning for the universal shape of the curve.

The issue of specimen size is directly applicable to surveillance specimens, even to those previously tested and which might be reconstituted. Questions regarding constraint limits for the Master Curve method and the pre-cracked Charpy (PCVN) specimen are still not very clear.

Since, at present, no microstructural technique has the capability to identify all irradiation-induced microstructural features, therefore a combination of FEGSTEM, 3D-AP and SANS is being used to ascertain complementary data on both precipitation and matrix chemistry of irradiated materials. Hence there is a need for development of more sophisticated experimental techniques for in depth analysis of metallic microstructures.

Lastly, while the fusion reactor is still in the development stage, it is more likely that the use of fission reactors would be continued for decades to come [55]. It is therefore imperative to continue the research on RPV steels to ensure safe operation and more accurate life assessment of existing large fleet of NPP as well as those which would be commissioned in future.

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Table 1. Alloying Elements in RPV steels.

Alloying Elements	Weight Percent
Carbon	0.05 – 0.2
Manganese	0.7 – 1.6
Molybdenum	0.4 – 0.6
Nickel	2.0 – 1.4
Silicon	0.2 – 0.6
Chromium	0.05 – 0.5

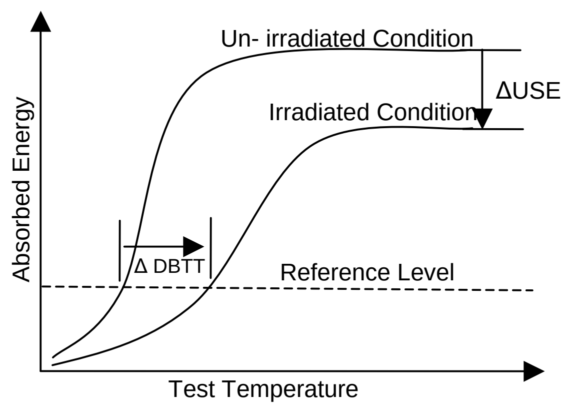

Fig.1. Schematic showing the influence of irradiation on DBTT.

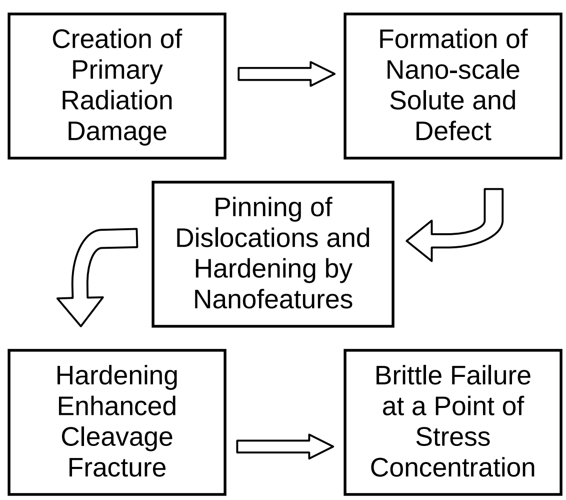

Fig.2. Sequence of basic embrittlement processes.

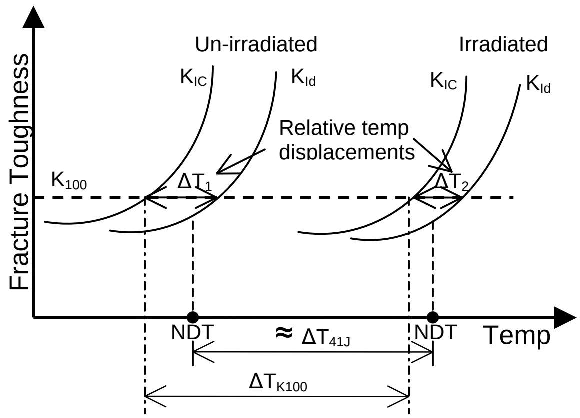

Fig.3. Schematic representation of the effect of irradiation on static and dynamic toughness curves.

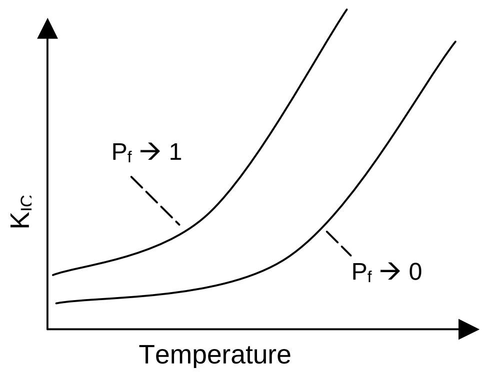

Fig.4. Schematic of curves used in probabilistic model to estimate the fracture toughness of a material.

