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U.S. NRC EMBRITTLEMENT DATA BASE (EDB)

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Wang, J. A.[1], Pace, J. V. III[1], and Rosseel, T. M.[1]

U.S. NRC Embrittlement Data Base (EDB)[2]

Reference: Wang, J. A., Pace, J. V. III, and Rosseel, T. M, "**U.S. NRC Embrittlement Data Base (EDB)**," *Reactror Dosimetry*, ASTM STP 1398, John G. Williams, David W. Vehar, Frank H. Ruddy and David Gilliam, Eds., American Society for Testing and Materials, West Conshohoken, PA, 2000.

Abstract: Large amounts of data obtained from surveillance capsules and test reactor experiments are needed, comprising many different materials and different irradiation conditions, to develop generally applicable damage prediction models that can be used for industry standards and regulatory guides. Version 1 of the Embrittlement Data Base (EDB) [*1*] is such a comprehensive collection of such data resulting from the merging of the Power Reactor Embrittlement Data Base (PR-EDB) [*2*] and the Test Reactor Embrittlement Data Base (TR-EDB) [*3*]. Fracture toughness data were also integrated into Version 1 of the EDB. The EDB data files are in dBASE format and can be accessed with a personal computer using the DOS or WINDOWS operating system. A utility program has been written to investigate radiation embrittlement using this data base. The utility program is used to retrieve and select specific data, manipulate data, display data to the screen or printer, and to fit and plot Charpy impact data.

Keyword: radiation embrittlement, database, power reactor, test reactor, fracture toughness

INTRODUCTION

The aging and degradation of light-water-reactor (LWR) pressure vessels is of particular concern because of their relevance to plant integrity and the magnitude of the expected irradiation embrittlement. The radiation embrittlement of reactor pressure vessel (RPV) materials depends on many different factors such as flux, fluence, fluence spectrum, irradiation temperature, pre- irradiation material history and its chemical composition. These factors must be considered to reliably predict the pressure-vessel embrittlement and to ensure the safe operation of the reactor. Based on embrittlement predictions, decisions must be made concerning operating parameters, and such issues as low-leakage-fuel management, possible life extension, and the need for annealing of the pressure vessel. Large amounts of data obtained from surveillance capsules and test reactor experiments are needed, comprising many different materials and different

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irradiation conditions, to develop generally applicable damage prediction models that can be used for industry standards and regulatory guides. Version 1 of the Embrittlement Data Base (EDB) is such a comprehensive collection of data resulting from the merging of the Power Reactor Embrittlement Data Base (PR-EDB) and the Test Reactor Embrittlement Data Base (TR-EDB). Fracture toughness data were also integrated into Version 1 of the EDB.

The scope and purpose of EDB program development, which is sponsored by the Nuclear Regulatory Commission (NRC) as a task of the Heavy-Section Steel Irradiation program can be summarized as follows:

1. Compile and verify a comprehensive collection of data from power reactor surveillance programs and test reactor irradiation experiments of pressure vessel materials from U.S. and foreign countries.
2. Provide software support for the use of the data base by furnishing programs and maintaining compatibility with commercially available software.
3. Facilitate the exploration and verification of embrittlement prediction models.
4. Facilitate the exploration and verification of the effects of annealing for pressure vessel life extension.
5. Interact with standards organizations to provide the technical bases for voluntary consensus standards that can be used in regulatory guides, Standard Review Plans, and ASME codes.

Examples of how the EDB data can be used to help resolve embrittlement issues include:

1. Phosphorous effect in low-copper materials.
2. Evaluation of irradiation temperature effects[4].
3. High Flux Isotope Reactor accelerated embrittlement study[5].
4. The development of radiation embrittlement models for U.S. power reactor[6].
5. Analysis of A302B and A533B correlation monitor materials.

CONTENT OF THE EDB

Three major categories of information are included in the EDB, namely, material history, irradiation environments, and mechanical test results. The data in these categories include:

1. Fluence (E > 1.0 MeV, E > 0.1 MeV, and dpa), irradiation time, and irradiation temperature for each capsule,
2. Charpy impact test results before and after irradiation, both for individual specimen and evaluation of transition temperature and upper-shelf energy,
3. Post-irradiated thermal annealed Charpy impact test results, both for individual specimen and evaluation of transition temperature and upper-shelf energy,
4. Tensile test results before and after irradiation,
5. Fracture mechanics' test results before and after irradiation,
6. Drop weight test data,
7. Chemistry data for each material,
8. Pre-irradiation heat treatment,
9. Data concerning the fabrication of weld material, and
10. Lead factor data.

The contents of the Charpy impact test results and tensile test results listed in the current version of EDB are stated below.

For power reactor data, the current EDB lists the 1,160 Charpy transition-temperature shift data points, which include 361 plates, 145 forgings, 118 correlation monitor materials, 280 welds, and 255 heat-affected-zone (HAZ) materials that were irradiated in 305 capsules from 105 commercial power reactors. The total number of Charpy test results listed in EDB is 20,495, of which 12,437 test results are from irradiated specimens. The total number of tensile test results is 4,052, of which 2,004 test results are from irradiated specimens.

For test reactor data, information is available for 1,308 different irradiated sets, 352 of which are from plates, 186 from forgings, 303 from correlation monitor materials, 396 from welds, and 71 from HAZs; and 268 different irradiated-and-annealed data sets, including 89 plates, 4 forgings, 11 correlation monitor materials, and 164 weld materials. The total number of Charpy test results listed in EDB is 11,082, where 5,852 test results are from irradiated Charpy specimens. The total number of tensile test results is 3,188, of which 1,452 test results are from irradiated tensile specimens.

The distributions of Charpy transition shift data for base and weld materials are illustrated in Figs. 1-4.

Fracture Toughness Data

The mechanical test results contained in PR-EDB and TR-EDB are Charpy impact and tensile test data. The transition-temperature approach, mainly relying on the Charpy impact test, is simple and has been used successfully. However, it has the limitation of being a temperature criterion rather than a more familiar stress criterion. Therefore, it cannot be used directly in the design. This shortcoming can be mended by including fracture-mechanics test results into EDB, which can offer a direct linkage to stress analysis and verify the relationships between the Charpy data and fracture toughness data. There are three categories of the fracture toughness data available from the reports: static fracture toughness, K_{IC} or K_{JC}, dynamics fracture toughness, K_{ID}, and arrested fracture toughness, K_{IA} data. The general specimens used in fracture toughness experiments are Single Edge Notch Bending specimens (SEB), Compact Tension (CT), Arc-Shaped Tension (AT), Disk-Shaped Compact Specimen (DCT), Crack-Line-Wedge-Loaded Specimen (CLWL, or WOL), Double Cantilever Beam Specimen (DCB), Center-Cracked Tension Panels (CCT). The experiments carried out on those specimens are under different criteria and experimental procedures, and are responsible for a particular kind of fracture toughness data. Thus, in EDB the three major categories of fracture toughness data are grouped into separated data files, and the criteria among the different type specimens are carefully distinguished. From the available reports, the most frequently used fracture toughness specimens are CT, WOL, DCB specimens and precrack Three Point Bend specimens. There are several schemes being used for the calculation of J_{IC} value, among different reports, beside ASME's specification, these methods need to be registered properly. Also there is a need to identify the different types of fracture behavior, and the validation of the test.

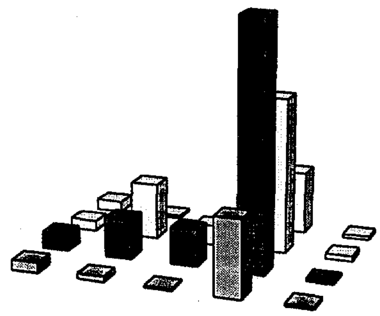

Fig. 1. Distribution of power reactor Charpy RT_{NDT} shift data for copper and nickel content for base and weld materials.

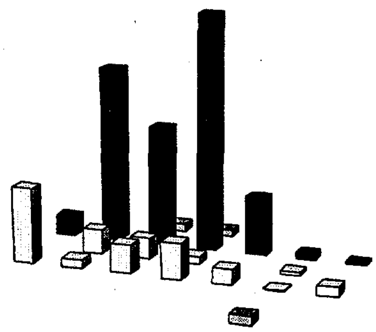

Fig. 2. Distribution of power reactor Charpy RT_{NDT} shift data for fluence and irradiation content for base and weld materials.

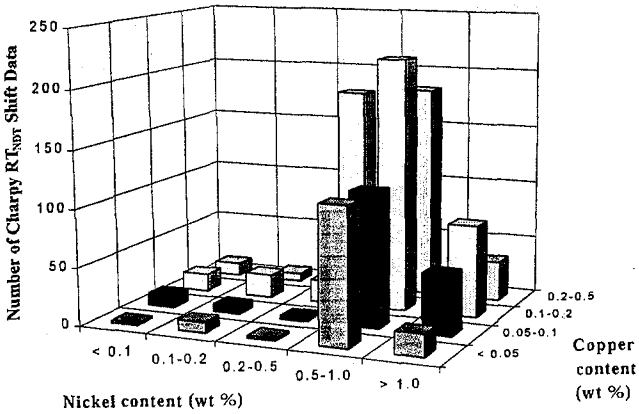

Fig. 3. Distribution of test reactor Charpy RT_{NDT} shift data for copper and nickel content for base and weld materials.

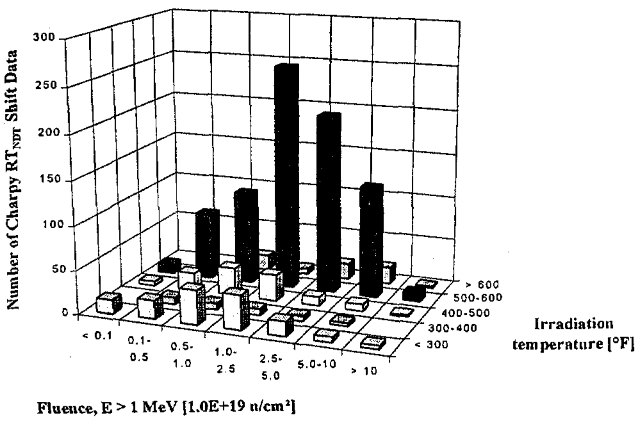

Fig. 4. Distribution of test reactor Charpy RT_{NDT} shift data for fluence and irradiation content for base and weld materials.

Since the data collections from different sources may be carried out on different machines and different experimental specifications, the detailed information of the test procedures and testing apparatus, such as machine type and capacity, and responsible engineers, etc., are needed to be integrated into the data base. Those data will allow the user to trace the original data source and identify any differences between different experimental environments and testing methodology. For example, several methods were used to determine the crack growth, such as the Crack Opening Displacement (COD) method, the Optical method, the Acoustic Emission Evaluation, or predicted by the compliance method. Since each may require different adjustments depending on the application to the particular specimens, that information needs to be evaluated carefully before being registered into data base. For dynamic or arrest fracture toughness experiment, in order to generate higher initial fracture toughness, K_{IC}, the CT or WOL specimens normally are modified with an embrittlement weld bead or duplex specimen. The additional modification among the specimens, such as pre-crack or side-grooves are also registered in EDB.

Currently, Phase 1 of this project has been completed, with three categories of the fracture toughness data available from the reports: static fracture toughness, K_{IC} or K_{JC}; dynamics fracture toughness, K_{ID} or K_{JD}; and arrested fracture toughness, K_{IA} data, having been integrated into EDB. The fracture toughness data base is a collection of fracture mechanics test results from the published documentation from HSST, HSSI, EPRI, and MEA research programs.

THE ARCHITECTURE OF EDB

EDB contains three major categories of data; namely, pre-irradiation material history, irradiation environments, and mechanical test results. The detailed architecture of EDB is illustrated in Fig. 5. The detailed descriptions of fracture mechanics specimen dimensions and the other nonstandard sizes of test specimens are stored in SPEC_GEO.dbf. The testing information, such as machine type, operation engineers, etc., is listed in SYSTEM.dbf.

The first category, on the left of Fig. 5, consists of results of material mechanical property tests. Charpy, both individual tests and results of curve fittings, tensile, drop weight nil-ductility-transition temperature (NDTT) data, and fracture toughness data are currently available. Each record in these files is uniquely characterized by the combination EXP_ID, PLANT_ID, CAPSULE, HEAT_ID, and SPEC_ORI. Other test results, such as instrumented Charpy, hardness, and dynamic tearing will also be included.

The second category, in the middle of Fig. 5, contains data describing the reactor and radiation environment for each surveillance capsule. The file REAC.dbf contains the fluence, the irradiation temperature and the irradiation time for each capsule. The file REAC.dbf is linked with the others via the key identifiers EXP_ID, PLANT_ID, and CAPSULE. The file REAC_GEO.dbf contains the detailed dimensions of the reactor structure, and the LEAD.dbf contains the lead factor data of pressure vessels of commercial power reactors. Under consideration is the development of "Dosimetry Data Base", which would contain detailed information on irradiation history, fluence spectra, and dosimetry data to allow for fluence determination by independent investigators, and

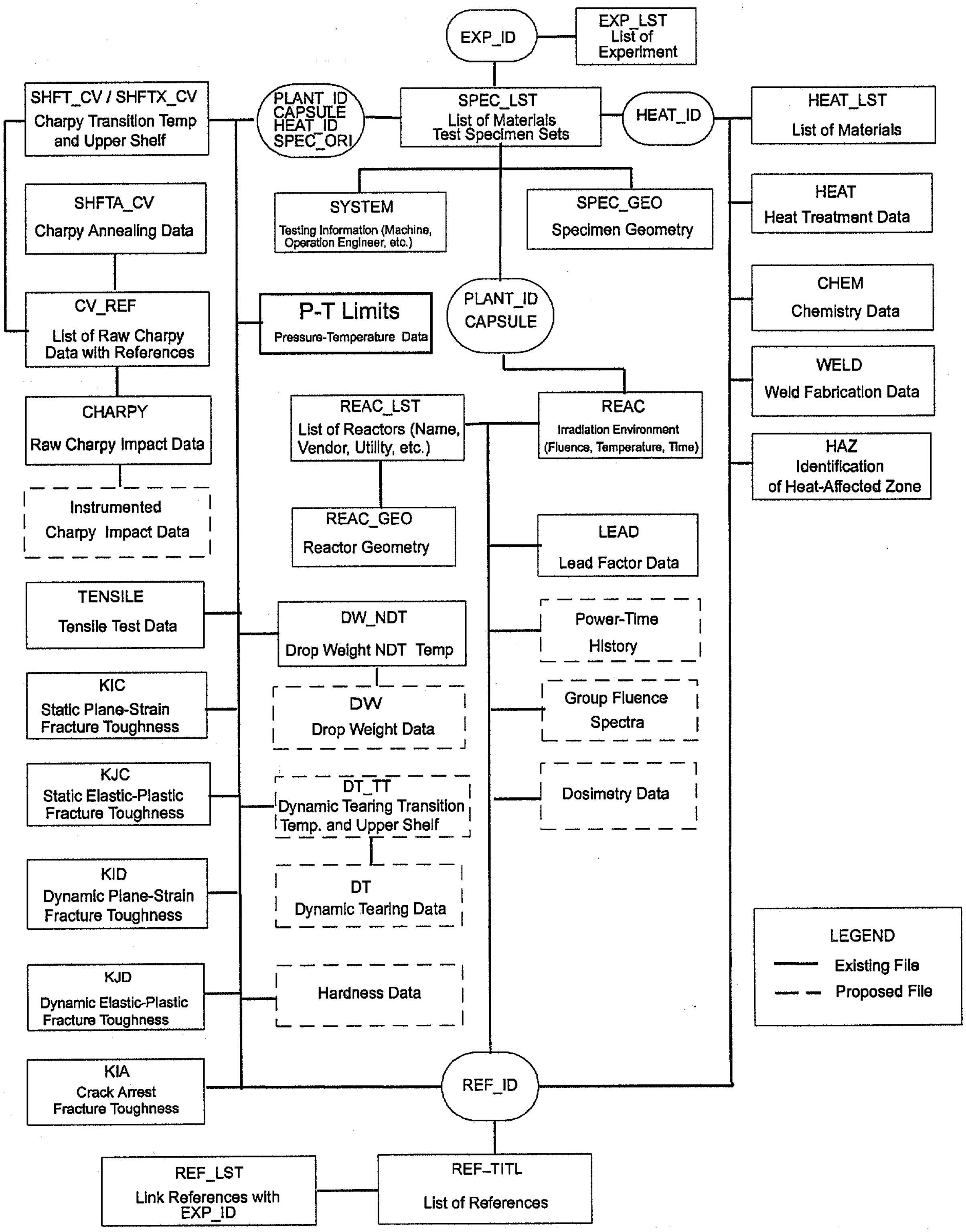

Fig. 5. Architecture of the Embrittlement Data Base (EDB).

more detailed investigation on impact of the rate effect, spectrum effect, and residual defects to the embrittlement prediction models.

The third category, on the right of Fig. 5 contains the information about the chemistry and fabrication of the materials used in the experiments or power reactor surveillance program.

The data files in the EDB are given in dBASE format and can be accessed with a personal computer using the DOS or WINDOWS operating system. A utility program has been written to investigate radiation embrittlement using this data base. The utility programs are used to retrieve and select specific data, manipulate data, display data to the screen or printer, and to fit and plot Charpy impact data.

FUTURE PLANS

The dosimetry, neutron spectrum, power-time history and microstructure data are targeted for inclusion in the EDB. Additional future work will include the development of "evaluated" data files and the automated program library to facilitate the investigations of issues affecting the integrity of RPVs.

Continued progress in materials science and engineering is increasingly dependent upon collaborative efforts between several different disciplines, as well as closer coordination among funding agencies and effective partnerships involving universities, industry, and national laboratories. In addition, because of the rapidly growing interdependence of the world's economies, partnerships are not only important at the national level but from an international point of view as well. Thus, the development of an integrated distributed database management (IDDM) system built upon the internet/WWW is needed. A central control system is recommended for the development of this IDDM system, which includes a central server with a common database, intellectual interface, and network gateways.

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US NRC Embrittlement Data Base

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Embrittlement Data Base

Version 1 of the Embrittlement Data Base (EDB) is a comprehensive collection of data resulting from the merging of the Power Reactor Embrittlement Data Base (PR-EDB) and the Test Reactor Embrittlement Data Base (TR-EDB). Fracture toughness data were also integrated into Version 1 of the EDB.

EDB Program Description

- **Computerized database of surveillance power reactors and experimental test reactors.**
- **Data are collected as reported into "Raw data files" and can be processed for tables, model fitting, and graphs.**
- **Traceability of data is maintained by references and pages; Quality assurance procedures were applied.**

Project Goals - Ultimate goals

- **Enhance the information flow**
- **Speed up the investigations**
- **Develop advanced materials**

Project Goals - High-level timing goals

- To compile and to verify the quality of EDB.
- To provide software to access the data.
- To explore or confirm embrittlement predictions, and
- To interact with organizations to provide the technical bases for voluntary consensus standards that can be used in regulatory guides, Standard Review Plans, and ASME Codes.

The Benefits of EDB

- **Provide the basis for improved Regulatory Guides.**
- **Enhance the evaluation of degradation of irradiated material.**
- **Improve the assessment on licensing issues.**
- **Develop new advanced materials.**

The EDB has been used in many radiation embrittlement studies, for examples:

1. **Analysis of the irradiated data for A302B and A533B correlation monitor materials.**
2. **Differences between the measured ΔRT_{NDT} in PR-EDB with the values predicted by Reg. Guide 1,99, Rev. 2, for base and weld materials.**
3. **The phosphorus effect in low-copper content materials.**
4. **Sensitivity of specimen orientation to radiation embrittlement.**
5. **Check if test results from LT specimens reduced to 65% of their value provided conservative estimates of the expected value from TL specimens.**
6. **Raw Charpy data curve fitting procedures.**
7. **Comparison of Reg. Guide 1.99, Rev. 2's model with French FIM's model.**

EDB used in Embrittlement Studies (con't)

8. Metallurgical and irradiation effects study for Yankee Rowe's reactor related events.
9. Evaluation of irradiation temperature effects.
10. Verification of initial RTNDT and ART per ASME Code and Reg.Guide 1.99, Rev. 2.
11. Determination of Pressure-Temperature Limits curves for commercial power reactors.
12. Background study for Reg. Guide 1.99, Rev. 2.
13. Residual study on the impact of improvement of fluence evaluation to R.G. 1.99, Rev. 2.
14. HFIR accelerated embrittlement study.
15. Development of radiation embrittlement prediction models for U.S. power reactors.

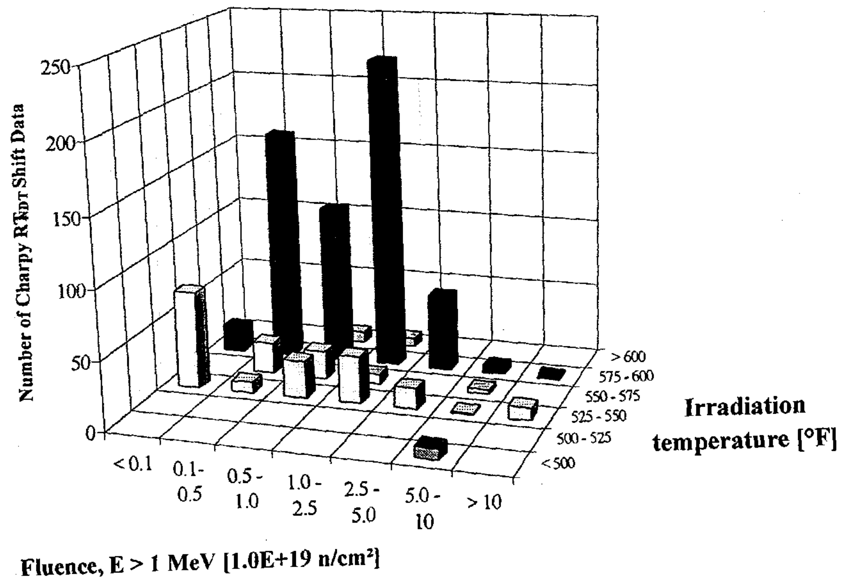
EDB Data Content

Power Reactor Data

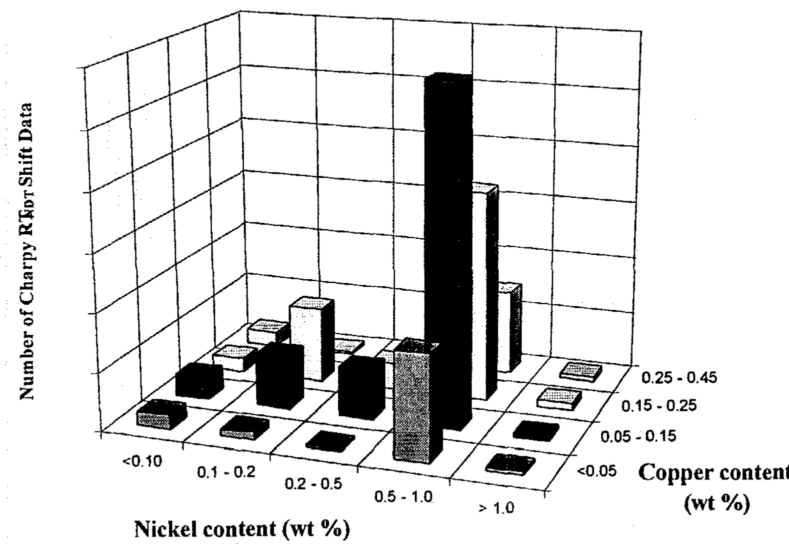
The current EDB lists the 1,160 Charpy transition-temperature shift data points, which include 361 plates, 145 forgings, 118 correlation monitor materials, 280 welds, and 255 heat-affected-zone materials that were irradiated in 305 capsules from 105 commercial power reactors. The total number of Charpy test results listed in EDB is 20495, where 12437 test results are from irradiated Charpy specimens.

The total number of tensile test results is 4052, where 2004 test results are from irradiated tensile specimens

Distribution of Power Reactor Charpy RT_{NDT} Shift Data for Base and Weld Materials



Distribution of Power Reactor Charpy RT_{NDT} Shift Data for Base and Weld Materials



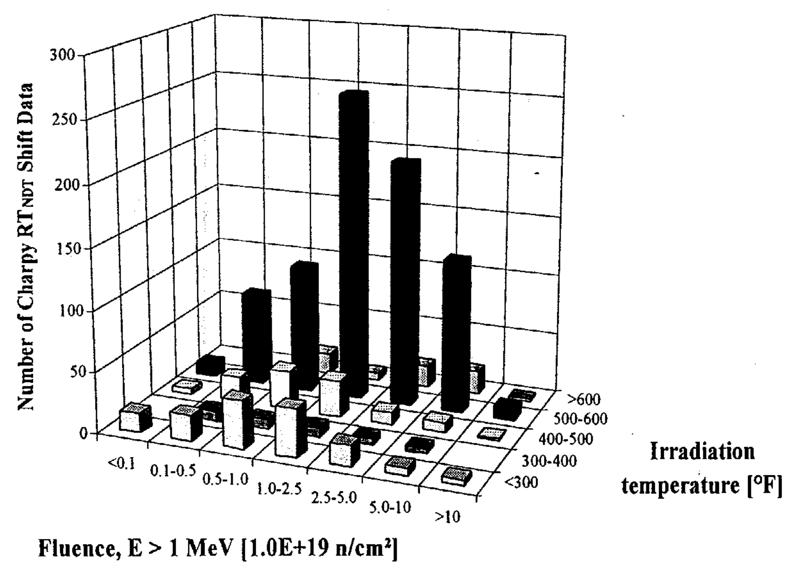
EDB Data Content

Test Reactor Data

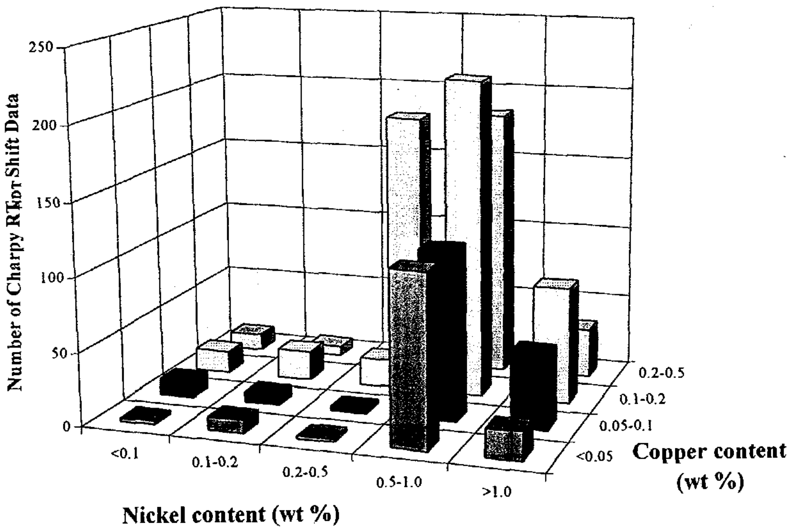
Information is available for 1,308 different irradiated sets, 352 of which are from plates, 186 from forgings, 303 from correlation monitor materials, 396 from welds, and 71 from HAZs; and 268 different irradiated-and-annealed data sets, including 89 plates, 4 forgings, 11 correlation monitor materials, and 164 weld materials. The total number of Charpy test results listed in EDB is 11082, where 5852 test results are from irradiated Charpy specimens.

The total number of tensile test results is 3188, where 1452 test results are from irradiated tensile specimens.

Distribution of Test Reactor Charpy RT_{NDT} Shift Data for Base and Weld Materials



Distribution of Test Reactor Charpy RT_{NDT} Shift Data for Base and Weld Materials



EDB Data Content

GROUP DATA	SUBGROUP DATA	DATA FILES (.dbf)
Material Identification	• Material Chemistry • Material Supplier • Utility Supplying Data • Base Material Technology • Weld Material Technology • HAZ Material Technology	CHEM HEAT_LST REAC_LST HEAT WELD HAZ
Aging History	• Irradiation Environment • Thermal Aging Environment • Power Time History • Reactor Geometry • RPV fluence • Pressure-Temperature Limits	REAC REAC POWER_H REAC_GEO LEAD P_T**
Mechanical Testing	• Tensile Testing Results • Charpy-V Impact Testing • Instrumented Charpy Data • Static Fracture Testing • Dynamic Fracture Testing • Drop Weight Testing • Dynamic Tearing Test • Hardness Testing • Charpy Transition & Hyperbolic Tangent Fit • Charpy Annealing Data • Fracture Toughness Fit • System Information	TENSILE CHARPY INST_CV KIC, KJC KID, KJD DW, NDTT DT, DT_TT HARDNESS* SHFT_CV & RAW_C_RS SHFTA_CV SHFT_KI* SYSTEM*
References	List of References List of Related References	REF_LST REF_TITL
Metallography &NDE Testing	Metallography Pictures & Other Nondestructive Tests	MET_PIC* ULTASONIC* ....
Collected Curves	ASCII Diagrams of Data Digitalized Pictures of Data	Instrumented Charpy data

*only data structures are available
** data format was designed for PT_LIM software

FUTURE EDB PLANS

The dosimetry, neutron spectrum, power-time history and microstructure data are targeted for inclusion in the EDB. Additional future effort will include the development of "evaluated" data files and the Automated Program Library (APL) to facilitate and speed up the investigations on issues regarding the integrity of RPVs.

APL Benefits: Speed up Updating Procedures and Decision Making Processes

- **Updating of analyses whenever new data or new assumptions for the analysis arise.**
- **Follow-up studies with refined models, optimizing procedures, exploring consequences in what-if scenarios.**
- **Documentation and opportunity for critical review by NRC or other affected parties.**

Future EDB Utility Upgrade

- **Operating under <u>Windows environments</u>;**
- **Retrieving, linking, and streamlining raw data to generate <u>processed data files</u>;**
- **Developing special routines to incorporate "<u>what-if scenarios</u>" into data selection procedures and analysis;**
- **Built-in routines to <u>automate the procedures</u> for updating analysis, for follow-up studies, and updating report.**

Future Vision on Database Management

- **New technology being used:**

  The Internet and electronic mail, WWW, PC.

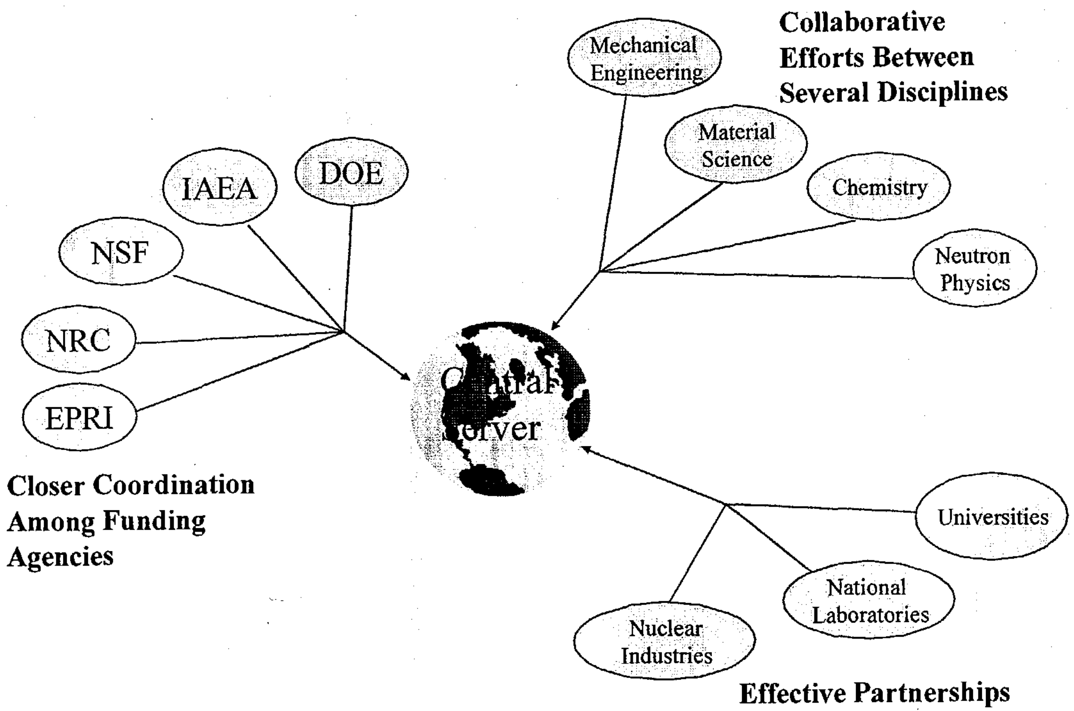
- **Standards being adopted:**

  Language - STEP, XML, Relational Database,...
  Testing Standards, Material Standards,..

- **CPED/ORNL has computing facility and personnel to develop a Central Server for the development of Integrated Distributed Database Management System (IDDMS).**

Future Vision on Database Management

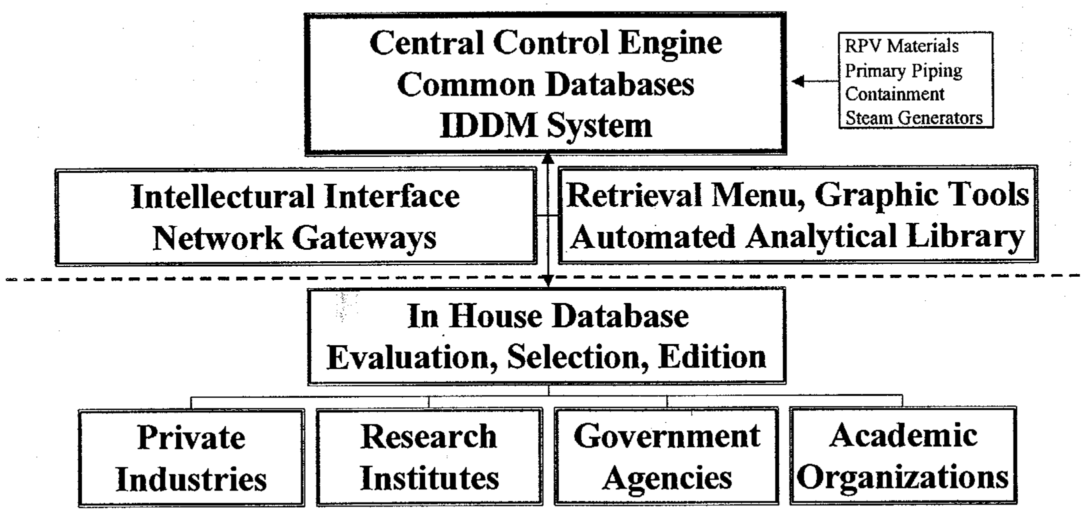
Continued progress in materials science and engineering depend on collaborative efforts between several different disciplines, as well as closer coordination among funding agencies and effective partnerships involving universities, industries, and national laboratories.


Collaborative
Efforts Between
Several Disciplines
Mechanical
Engineering
Material
Science
Chemistry
Neutron
Physics
IAEA
DOE
NSF
NRC
EPRI
Closer Coordination
Among Funding
Agencies
Universities
National
Laboratories
Nuclear
Industries
Effective Partnerships

The Object of Central Server

Enable a harmonious cooperation among heterogeneous hardware and software systems carries the potential for great increase in productivity and improvement in application processing.

Integrated Distributed Database Management System



Characteristics of IDDMS

- **Easy accessible information system**
- **Large material databases**
- **Effective computing facilities**
- **User friendly interface and network**
- **Common database central system**
- **Supporting analytical library**