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JAERI'S CONTRIBUTION TO THE IAEA COORDINATED RESEARCH PROGRAMME ON "ASSURING STRUCTURAL INTEGRITY OF REACTOR PRESSURE VESSELS" (CRP-Ⅳ)
- FINAL REPORT -
(CONTRACT RESEARCH)

May 2000

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JAERI's Contribution to the IAEA Coordinated Research Programme on "Assuring Structural Integrity of Reactor Pressure Vessels" (CRP-IV) - Final Report - (Contract Research)

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According to the Research Agreement No. 9736 between the IAEA and the JAERI, we commenced the test program for the IAEA Coordinated Research Program (CRP) on "Assuring Structural Integrity of Reactor Pressure Vessels" at JAERI in September 1997. For the program, we received one block of the IAEA reference material JRQ from the IAEA CRP coordinator in June 1997. The test program has been conducted using the JRQ block and additional materials (Steels A and B) from our own program having a similar object with the CRP.

The CRP consists of two parts; a mandatory part and an optional part. For the mandatory part of the JAERI program, instrumented Charpy impact tests and fracture toughness tests using precracked Charpy-v (PCCv) specimens were performed. As the optional part, neutron irradiation to specimens of JRQ was conducted at JMTR by using two capsules. In this report, the results of the mandatory part and irradiated Charpy and PCCv specimens of JRQ from capsule No.1 as well as those of Steel A and Steel B were described.

The following conclusions were drawn; 1) the data form Charpy impact and fracture toughness tests of JRQ agreed well with the data in the CRP-3, 2) the scatter of fracture toughness of JRQ is relatively large, i. e., the Weibull slope "b" is less than 3, 3) the reference

This report includes the test results obtained under the contract between JAERI and the Science and Technology Agency of Japan under the auspices of the special account law for electric power development promotion.

temperature T_0 from PCCv is in good agreement with T_0 from 1T-Compact Tension (CT) when the tests are performed at the recommended temperature or the data has no invalid data, 4) the reference temperature T_0 after neutron irradiation can be determined with six to eight specimens at the recommended temperature and 5) the shift of the reference temperature T_0 is almost equivalent to the shift of Charpy transition temperature, but affected by the treatment of the highest data and testing temperature.

Further studies on the fracture toughness evaluation are necessary concerning the treatment of outlier, temperature dependence after irradiation and multi-temperature analysis.

Keywords:
Reactor Pressure Vessel, Integrity, Surveillance, Irradiation Embrittlement, Fracture Toughness, Charpy, Master Curve

JAERI Research 2000-022

「原子炉圧力容器の健全性確保」に関するIAEA協力研究(CRP-IV)における原研の試験結果－最終報告書
(受託研究)

日本原子力研究所東海研究所安全性試験研究センター原子炉安全工学部
鬼沢　邦雄・鈴木　雅秀

(2000年4月5日受理)

原研では、1997年9月から、「原子炉圧力容器の健全性確保」に関するIAEAとの協力研究を開始した。この研究では、IAEAから共通鋼材JRQを受領して使用した。また、JRQとともに本協力研究と関連して原研で実施している受託研究で使用している鋼材A及びBも使用して試験を進めた。

本協力研究は、必須項目と選択項目の2つに分けられている。必須項目として、計装シャルピー衝撃試験及びシャルピー型試験片による破壊靭性試験を実施した。選択項目として、原研ではJRQの試験片に対する中性子照射をJMTRにおいて行い、東海研ホットラボにおいて照射後試験を実施した。本報告書は、鋼材A及びBならびにJRQに対して実施した必須項目試験及び選択項目試験の結果をまとめたものである。本協力研究で得られた結論は以下の通りである。

1) 今回得られたJRQのシャルピー特性及び破壊靭性データは、前期CRPのデータと良く一致した。

2) JRQの破壊靭性データは、ワイブル形状母数bが3以下(理論値は4)となり、ばらつきはかなり大きい。

3) シャルピー型破壊靭性試験片から求めた破壊靭性参照温度T_0は、ASTMの推奨温度または無効データが無い温度で試験を実施した場合、1インチ厚コンパクト(1TCT)試験片から求めたT_0と良く一致する。

4) 照射後の参照温度T_0は、推奨温度での6～8本の試験片により求められる。

5) 照射による参照温度T_0のシフトは、シャルピー遷移温度のシフトとほぼ等しいが、逸脱データの取扱い試験温度により影響される。

逸脱したデータの取扱い、照射後の破壊靭性の温度依存性や複数試験温度のデータ解析法などについては、さらなる試験が必要である。

本報告書は、電源開発促進対策特別会計法に基づき、科学技術庁からの委託によって得られた試験研究の成果を含む。

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1. Introduction

In September 1996, the IAEA initiated a coordinated research program (CRP) on "Assuring Structural Integrity of Reactor Pressure Vessels" with a collaboration of 24 organizations from 20 different countries. This CRP is a fourth phase of the program related to irradiation embrittlement of reactor pressure vessel (RPV) steels. The purpose of the CRP is 1) to facilitate the international exchange of information and to provide practical guidance in the field of monitoring RPV material behavior, and 2) to develop and assess a uniform procedure of testing small size (Charpy type) specimens applicable to surveillance program with the aim of obtaining fracture toughness data necessary for the assessment of RPV structural integrity. The main objective of this CRP is to develop and validate a procedure for fracture toughness testing with small specimens applicable to surveillance program.

The Japan Atomic Energy Research Institute (JAERI) took part in this IAEA CRP on September 1997. For this CRP, the Research Agreement No. 9736 between the IAEA and the JAERI was signed by both representatives.

The objective of the JAERI program for this CRP is to evaluate the fracture toughness of some Japanese RPV steels before and after neutron irradiation using Charpy size specimens. Investigation on the non-destructive measurements for the irradiation embrittlement is also conducted.

The JAERI program consists of two parts: a mandatory part and an optional part. The mandatory part includes mechanical property tests for unirradiated materials. The optional part includes irradiation at JMTR, post-irradiation tests for mechanical properties such as instrumented Charpy impact and fracture toughness, and an annealing study for embrittlement recovery. Non-destructive measurements of irradiation embrittlement are also performed before and after neutron irradiation.

This paper summarizes the overall program at JAERI and the results obtained from the JAERI program in the framework of this CRP.

2. JAERI Program and Materials Used

Table 1 shows the overall program of JAERI for this phase of CRP. In addition to the mandatory part of the CRP, several experiments, such as sub-size Charpy testing, nondestructive measurements, were to be performed. However, the preparatory works for those additional experiments were not fully performed within the limited time schedule of the CRP. Those experiments will be performed in the near future.

IAEA reference material JRQ was used for both the mandatory part and the optional part of the program. One block of JRQ plate (ID: 5JRQ43), which was distributed from the program coordinator, is used for the program. In addition, two kinds of ASTM A533B-1 steels are used for both parts[1]. One is an irradiation sensitive steel, called Steel A*, that contains almost the same impurities as those in the JRQ. Another is a modern steel, called Steel B*, having very low copper and phosphorus contents. Table 2 shows the chemical composition and tensile properties at room temperature of the materials used in this program. The RT_{NDT} values determined by drop weight tests are also listed in the table.

The sampling positions of specimens in the JRQ block are shown in Figure 1. Test specimens were machined from six layers (three layers in each side) within the portion of 45-85 mm from each surface of the block. Specimens of Steels A and B (both 200 mm thick) were sampled from quarter thickness positions of the materials.

Table 1--Test matrix of JAERI program for the IAEA CRP-IV.

		Item	Material	5JRQ43	Steel A	Steel B
Mandatory part		Charpy Impact		O	O	O
		Tensile		O	O	O
		Fracture toughness	PCCv	O	O	O
Optional part	As-received condition	Fracture toughness	CT		O	O
		Sub-size Charpy		(O)	(O)	(O)
		NDE*		(O)	(O)	
		Microstructure		(O)	(O)	(O)
	Post-Irradiation at JMTR	Tensile		O	O	O
		Charpy Impact		O	O	O
		Fracture toughness (PCCv)		O	O	O
		Sub-size Charpy		(O)	(O)	
		NDE*		(O)	(O)	
		Microstructure		(O)	(O)	(O)

( ): planned

*NDE: Non-destructive evaluation

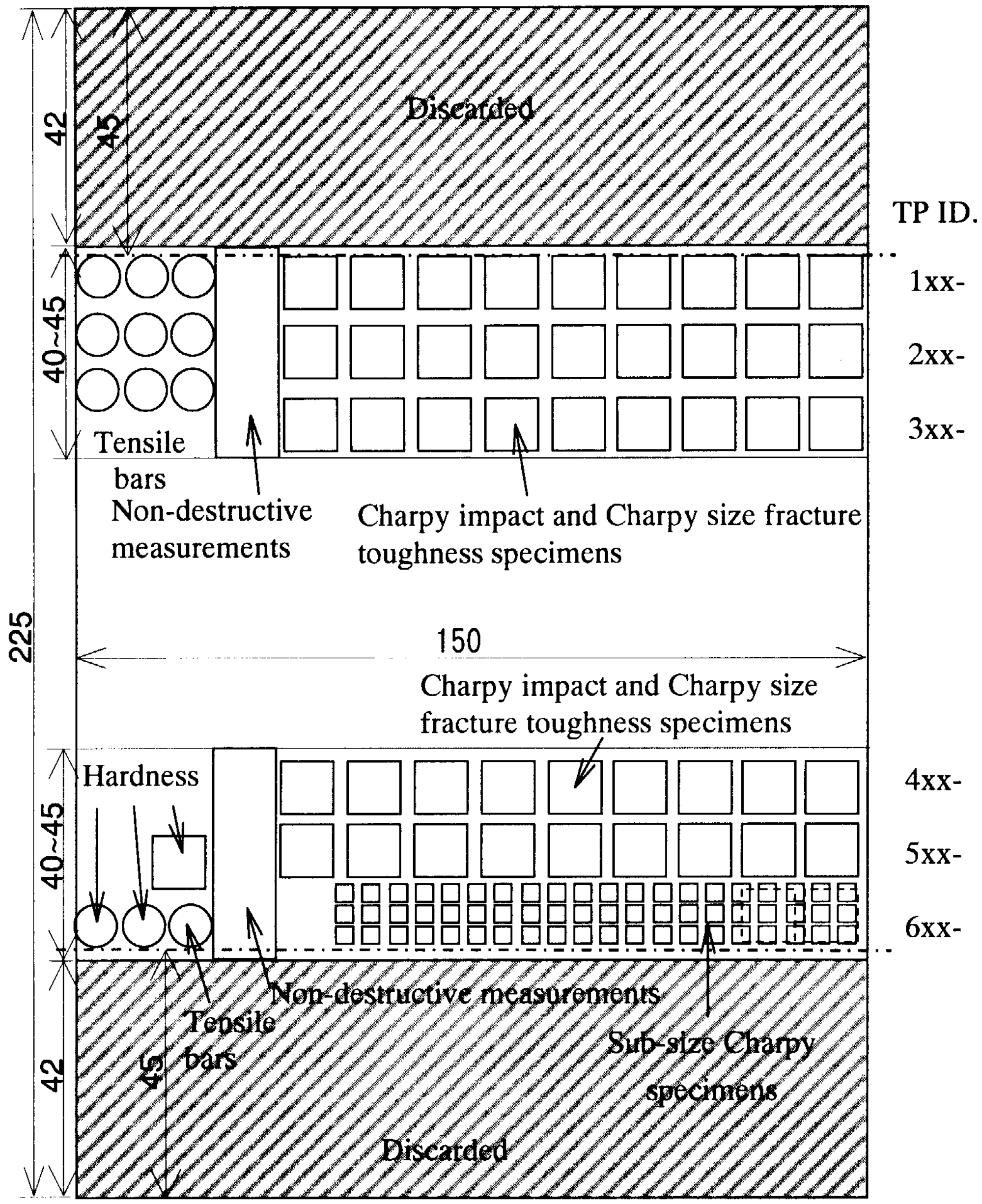
* The materials designated Steel A and Steel B were manufactured under the contract between the JAERI and Science and Technology Agency of Japan.

Table 2--Chemical compositions and mechanical properties at room temperature of materials used in this study. (wt.%)

Material	C	Si	Mn	P	S	Ni	Cr	Cu	Mo
JRQ	0.18	0.24	1.42	0.017	0.004	0.84	0.12	0.14	0.51
Steel A	0.19	0.30	1.30	0.015	0.010	0.68	0.17	0.16	0.53
Steel B	0.19	0.19	1.43	0.004	0.001	0.65	0.13	0.04	0.50

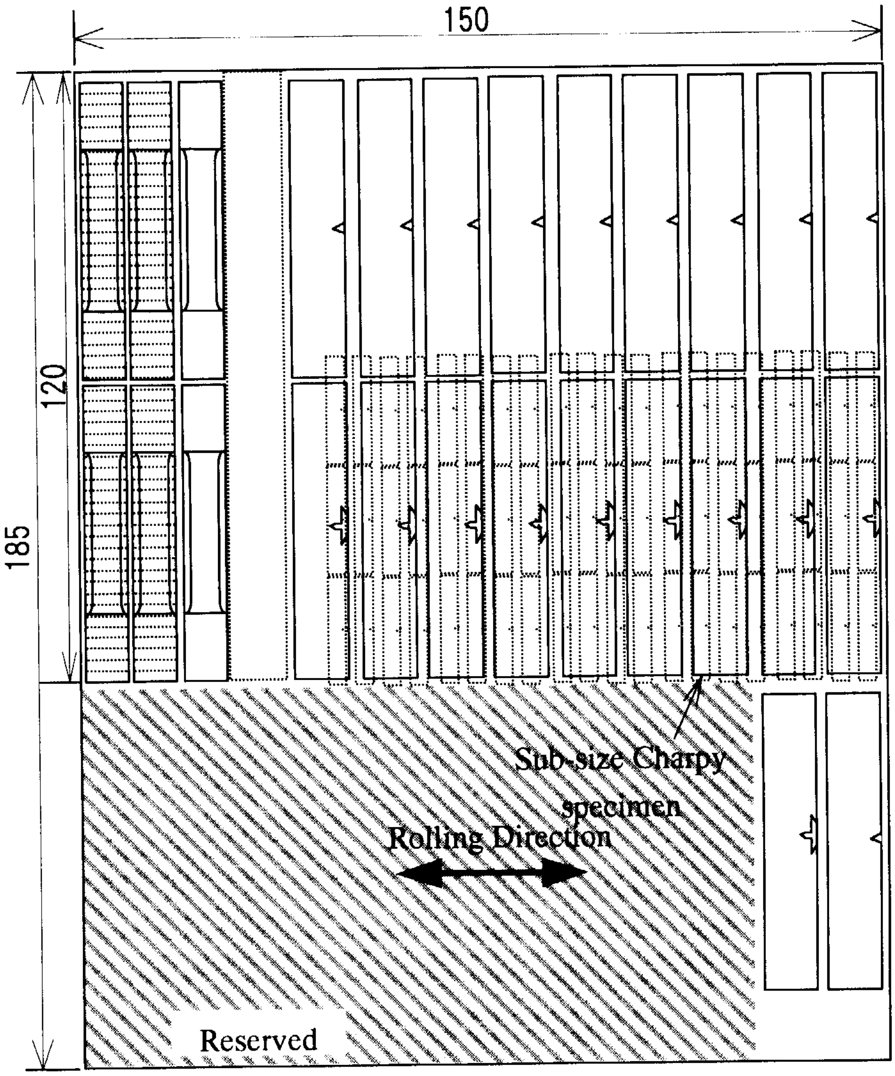
Material	σ_{ys} (MPa)	σ_{uts} (MPa)	Elongation (%)	RT_{NDT} (°C)
JRQ	488	623	22.9	-15
Steel A	469	612	26.4	-35
Steel B	462	597	24.9	-45

(Average of three specimens)



(a) Section view

Figure 1--Cutting scheme for test specimens from JRQ block. (5JRQ43)



(b) Top view

Figure 1-- (continued)

3. Test Procedure

3.1 Mandatory Part

3.1.1 Charpy Impact Test

An instrumented Charpy-V impact test machine is used. The capacity of the machine is 300 J. The hammer tup has 2 mm radius according to the JIS standard(2) that is similar to the ISO standard. The hammer speed at impact is ~5 m/s. The geometry and dimension of specimen are shown in Figure 2(a). All Charpy V-notch specimens are machined to T-L orientation. The instrumented load and deflection data are acquired through a high speed A/D converter into a PC.

Specimens are set in the temperature control bath for 10 minutes before testing. The media in the bath are an alcohol for a low temperature test and a silicon oil for a high temperature test. An automated specimen transfer system is used to keep the testing conditions for all specimens equal and to minimize the temperature change of specimen during transferring. The average time to impact the specimen after the removal from the temperature control bath is ~3.5 seconds.

3.1.2 Fracture Toughness Test

Static fracture toughness tests under three point bending using precracked Charpy-V (PCCv) specimens are performed using a 100 kN mechanical-servo type testing machine. Specimen preparation and testing are conducted according to the ASTM standard(3,4). The geometry and dimension of PCCv specimen are shown in Figure 2(b). All PCCv specimens for fracture toughness tests are machined to T-L orientation. All specimens are side-grooved by 10 % on each side of the specimen after precracking. A calibrated load cell and a clip gauge are used for measuring applied load and load point displacement, respectively. The unloading elastic compliance method was not applied.

Prior to testing, the temperature of a test specimen and the fixture inside a testing chamber was kept at the target temperature for 20 minutes. Cold nitrogen gas is injected into the chamber for low temperature testing. The temperature distribution around the specimen is measured by three calibrated thermocouples. A thermocouple is attached on the upper fixture. The others are buried in the dummy specimens and located close to the test specimen. The temperature of all thermocouples and hence the test specimen is then controlled at the target temperature within a variation of 1°C during testing.

3.1.3 Tensile Test

Static tensile tests are performed using a 10 kN universal testing machine or a 100 kN mechanical-servo type testing machine. The geometry and dimension of the specimen are shown in Figure 2(c). Tensile specimens are machined to have a T-direction. Test temperatures are chosen corresponding to the temperature for fracture toughness testing.

3.2 Optional Part

The following tests were planned to perform in the framework of this CRP. Irradiation at JMTR and post-irradiation tests were completed. However, some tests were delayed by the preparatory work for the instrumentations and/or the equipment. Those tests will be performed in the near future.

3.2.1 Sub-size Charpy Impact Test

Sub-size Charpy impact testing will be performed using one-third size specimens shown in Figure 2 (d). The testing machine is under development at this moment. Therefore, the sub-size Charpy impact tests will be done in 2000-2001.

3.2.2 Non-destructive Measurement

As a reference property for non-destructive measurements of irradiation embrittlement, some kinds of physical properties will be measured; such as magnetic[5] and ultra-sonic properties[6].

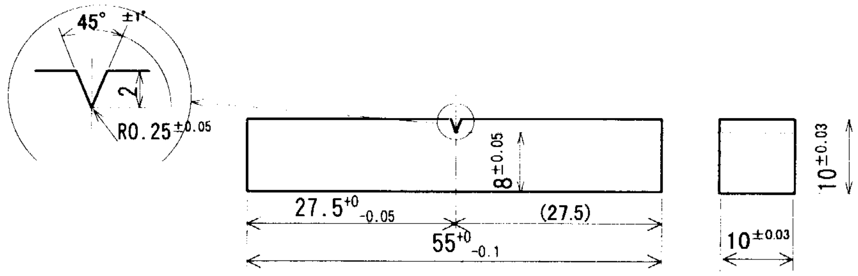
3.2.3 Irradiation at JMTR and Post-irradiation Test

To study an irradiation effect on each mechanical property mentioned in 3.1, test specimens of JRQ are irradiated in Japan Materials Testing Reactor[7] (JMTR, thermal output 50 MW) at Oarai Research Establishment of JAERI. The condition and specimens for irradiation is described in sections 6.1 and 6.2.

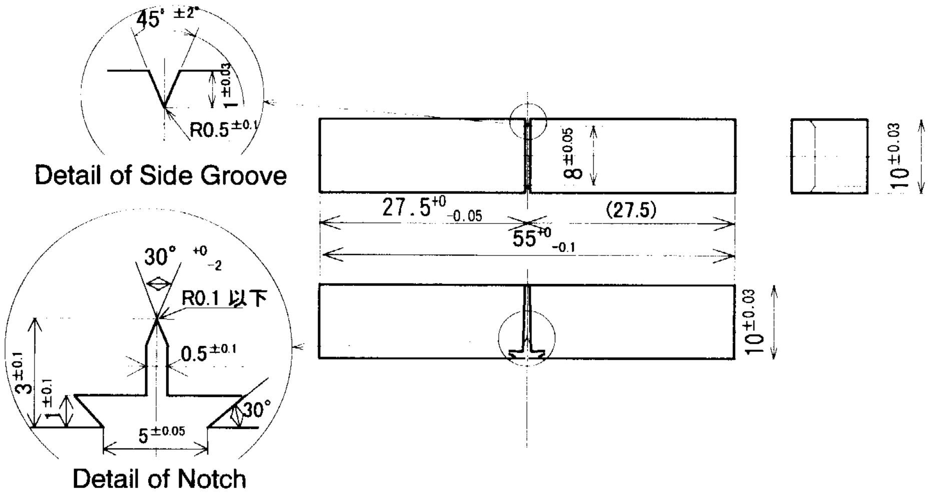
The post-irradiation tests will be done mainly in the Research Hot Laboratory of Tokai Research Establishment at JAERI. Tensile, instrumented Charpy impact and static fracture toughness tests are performed in the hot cell. The test procedures for the post-irradiation tests are the same as those for unirradiated specimens.

3.2.4 Annealing Study

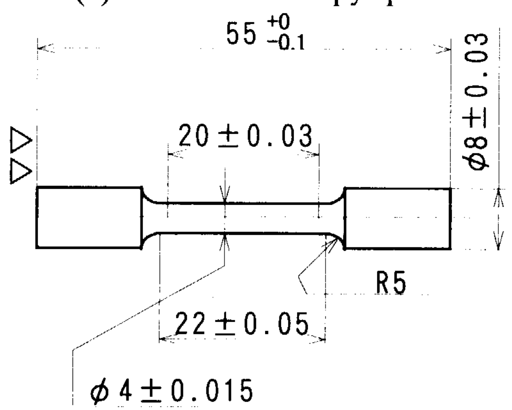
To study the recovery of irradiation effects on mechanical properties, some kinds of annealing treatments will be applied to the irradiated specimens. After annealing, hardness, tensile, sub-size Charpy impact and fracture toughness tests will be performed.



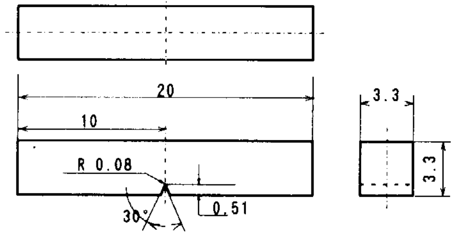
(a) Charpy impact specimen



(b) Precracked Charpy specimen



(c) Tensile specimen



(d) Sub-size Charpy specimen

Figure 2--Geometry and dimensions of test specimens.

4. Time Schedule

In June 1997, we received the JRQ block, designated as 5JRQ43, from the IAEA CRP coordinator. After machining of specimens, unirradiated specimens were tested for the mandatory part of the program. The efforts for the optional part were also initiated. Two capsules were manufactured for JMTR irradiation. The capsule No.1 was irradiated from June to July 1998. The post-irradiation tests for the specimens irradiated in the capsule No.1 have been performed since November 1998. The capsule No.2 was irradiated from November 1998 to March 1999 at JMTR. Post irradiation tests for the specimens in the capsule No.2 was started in November 1999. The time schedule and the milestones of the JAERI program are shown in Table 3.

Table 3--Time schedule and milestones of the JAERI program.

Item CY	1997	1998	1999
Material Receipt	Δ		
Specimen Preparation	●—►		
Reference Testing	●———	——►	
Irradiation (JMTR) No.1		●►	
Irradiation (JMTR) No.2		●—	—►
Post-Irradiation Testing No.1		●—	—►
Post-Irradiation Testing No.2			●——►
Annealing Study			●-►
Other Optional Tests			●-►
Reporting		●►	●—►
Meeting	⊗	⊗	⊗

Irradiation No.1: ~2.5×10^{19} n/cm^2 (E>1MeV)
Irradiation No.2: ~11×10^{19} n/cm^2 (E>1MeV)

5. Results from Mandatory Part

5.1 Instrumented Charpy Impact Test

Eighteen specimens of JRQ were tested in the range from –80°C to 120°C. Test results are listed in Attachment. Charpy transition curve was obtained by fitting the data to the following hyperbolic tangent equation;

$$Cv = \frac{US}{2} \cdot \left[1 + \tanh\left\{\frac{(T - T_{cv})}{C}\right\}\right] \quad (1)$$

where Cv: Absorbed energy, Lateral expansion or Shear area,
US: Mean value at upper shelf range for each Charpy property,
C, T_{cv}: Fitting constants.

Figure 3 shows Charpy test results for JRQ as well as the Charpy indexing temperatures obtained from equation (1). The transition temperatures at 28 J and 41 J of absorbed energy are -37°C and -25°C, respectively. Figure 3 also includes Charpy test results obtained from the previous CRP-3 efforts at JAERI. Although the specimens in CRP-3 tests were machined from a different position of the block, both data sets are agreed very well.

Figure 4 shows Charpy test results for Steel A. The figure includes JAERI data as well as original data obtained from specimens machined at the top and bottom portions by the steel fabricator. There can be seen no difference in the data, which means the homogeneity of the material. The transition temperatures at 28 J and 41 J of absorbed energy are -54°C and -42°C, respectively.

Figure 5 shows Charpy test results for Steel B. The figure also includes JAERI data as well as the original data by the steel fabricator. The data shows higher upper shelf energy and lower transition temperature than JRQ and Steel A, which means a good quality of the material. However, the difference between the original and JAERI data is seen slightly in the transition regime. Based on JAERI data, the transition temperatures at 28 J and 41 J of absorbed energy are -68°C and -61°C, respectively.

All the indexing transition temperatures for three materials are listed in Table 4.

Load-time signals of instrumented Charpy impact tests for JRQ and Steel A are shown in Figure 6. Based on the signals, characteristic loads of Pgy, Pm, Piu and Pa are defined according to ASTM E636. The characteristic loads as a function of temperature, i.e., Charpy load diagrams, for JRQ, Steel A and Steel B are shown in Figure 7. The data of crack arrest load, Pa for JRQ are fitted to an exponential equation according to the reference (8). The temperature at 4 kN of Pa is calculated to be 39°C.

5.2 Fracture Toughness Test

Based on Charpy impact test results, the test temperature for fracture toughness evaluation was determined to be –80°C for JRQ. This temperature is very close to the recommended temperature by ASTM E1921, and the same as the main test temperature performed during and after the CRP-3 efforts at JAERI[9,10]. The fracture toughness tests for PCCv specimens of Steel A were performed at -100°C and -80°C. The testing temperature of -100°C corresponds to the recommended temperature by ASTM E1921. The tests for PCCv of Steel B were performed at -130°C and -110°C, since the recommended temperature was -118°C. For both Steels A and B, 1TCT and 4TCT specimens were tested in the transition temperature range to see the effect of specimen size.

The validity of fracture toughness data is evaluated by the following equation related to the specimen size requirement according to ASTM E1921.

$$K_{Jc} \leq \sqrt{\frac{E b_0 \sigma_{ys}}{30}} \qquad (2)$$

where E: Young's modulus

b_0: initial ligament size

σ_{ys}: yield strength at the test temperature

Every K_{Jc} datum that does not satisfy this equation is considered as invalid and should be used in a censoring procedure.

All eight PCCv specimens of JRQ were fractured by a cleavage mode at -80°C. All K_{Jc} data were valid based on the equation (2). The results are shown in Figure 8(a) and listed in Attachment. Test results obtained from previous phase of CRP are also shown in the figure. In order to determine the reference temperature T_0 according to ASTM E1921, the size adjustment scheme and the maximum likelihood method were applied to the data. The master curve and the tolerance bounds determined based on PCCv data were indicated in Figure 8(b). The T_0 determined from this study was -66°C, while previous T_0 based on PCCv data in the previous CRP was -65°C. These data were coincided completely. In addition, fracture toughness tests by 1TCT specimens were performed using another JRQ block for the previous CRP. Results are also shown in Figure 8 and data are listed in Attachment. The T_0 determined from 1TCT data was -66°C. This result is again the same as PCCv results.

Test results of ten PCCv specimens of Steel A are shown in Figure 9 and listed in Attachment. All K_{JC} data at -100°C are valid according to the equation (2). The analysis of these results provided a reference temperature T_0 of -70°C. The T_0 temperature obtained at -100°C is in good agreement with the mean T_0 (-67°C) calculated from the 1TCT results tested at -80°C and -50°C. Seventeen PCCv specimens of Steel A were also tested at -80°C and broken by cleavage mode. Five K_{Jc} data out of seventeen were invalid according to equation

(2). Therefore, the censoring scheme was applied to the data. The T_0 calculated from the PCCv data at -80°C was -82°C with data censoring, which was 15°C lower than that from 1TCT.

Ten PCCv specimens of Steel B were tested at -130°C and broken by cleavage mode. Results are listed in Attachment and shown in Figure 10. All data were valid per equation (2). The reference temperature T_0 calculated from PCCv data was -84°C. On the other hand, the mean T_0 from 1TCT specimens tested at -110°C and -80°C was -97°C. Therefore, slightly conservative T_0 was determined from PCCv specimens. However, in this case the test temperature is 46°C lower than the T_0 temperature. This means that the median K_{Jc} value is quite low (≅59 MPa√m), and that the test temperature is close to the lower-shelf temperature range. This gives us an increase in uncertainty to determine the T_0. Since ten specimens were tested, the number of data was satisfied with the requirement in E1921. It seems, nevertheless, that the test temperature was too low to determine T_0. The PCCv test results at -110°C are also shown in Figure 10(b). Three K_{Jc} values out of twelve were invalid in this case. Therefore, the censoring scheme was applied to the data. The T_0 calculated from these data at -110°C was -111°C which was 14°C lower than the T_0 from 1TCT. However, if we take the average of T_0 temperatures obtained at -110°C and -130°C (average T_0=-98°C) it is almost the same as the T_0 from 1TCT. Further analysis on the multi-temperature data would be necessary.

All the reference temperatures T_0 from PCCv data as well as T_0 from 1TCT data for three materials are listed in Table 4. When PCCv was tested at the ASTM recommended temperature, T_0 temperatures between PCCv and 1TCT are in good agreement. On the other hand, when PCCv were tested at higher temperature, the differences in T_0 temperatures between PCCv and 1TCT became significant, 15°C for Steels A and 14°C for Steel B. These are slightly large compared to the data in the reference (11), which reports the 10°C difference between PCCv and 1TCT. The reason for the difference in T_0 may be due to the higher test temperature for PCCv specimens than the recommendation where some invalid data were obtained and a data censoring was applied.

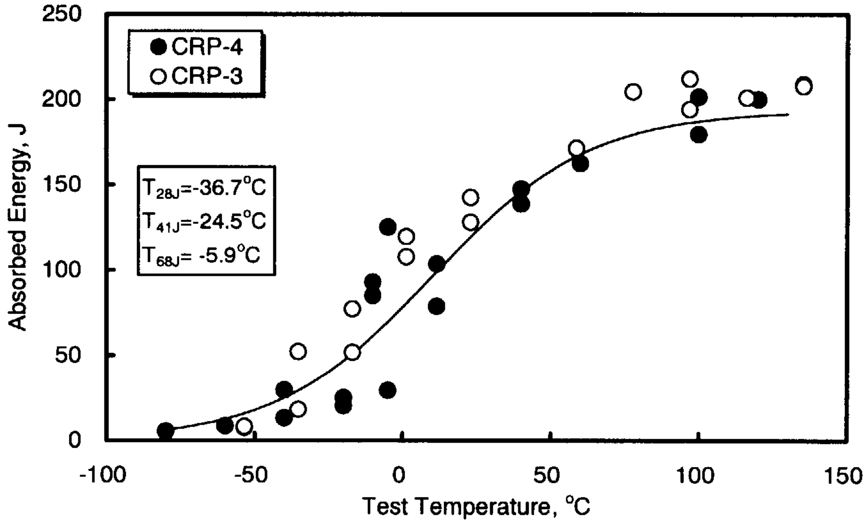
With regard to the data scatter, the JRQ data showed more variation than Steel A data. As shown in Figures 8 and 9, the lower bound data of JRQ correspond to 1% tolerance bound, while those of Steel A correspond to the 5% tolerance bound. The number of data are approximately the same (60~70). The lowest datum from PCCv of JRQ could be an outlier according to the ASTM standard, because the data point is less than the 2% lower bound confidence limit. Another outlier was found in the previous data set of JRQ obtained from CRP-3 tests at JAERI. The inhomogeneity of JRQ is also found in the reference (12). The lowest datum was anyway included in this analysis.

To see the scatter and the size effect of fracture toughness data, size-adjusted K_{JC} data of JRQ, Steel A and Steel B are shown in Figure 11. The vertical axis is a cumulative fracture probability calculated by the median ranking method. According to the ASTM standard, K_{min} was set to 20, and the scale parameter "b" for Weibull distribution was fitted by a least square method. A theoretical value of "b" is four based on the weakest link theory. However, the results of JRQ provided relatively small "b", indicating the larger scatter. The "b" value of PCCv data of Steel B at –110°C was also very low. In the latter case, the data number may not be sufficient and some data are invalid. However, the "b" value at -130°C agrees the theoretical value. In addition, the Weibull slopes of both PCCv and 1TCT of Steel A are approximately four. The difference in the Weibull slope from the theoretical value may affect the determination of lower bound toughness. Therefore, more data are necessary to quantify the scatter of fracture toughness and to establish the method for the lower bound toughness estimation. The treatment of the inhomogeneous material having a large data scatter should be an issue for further study on the master curve approach.

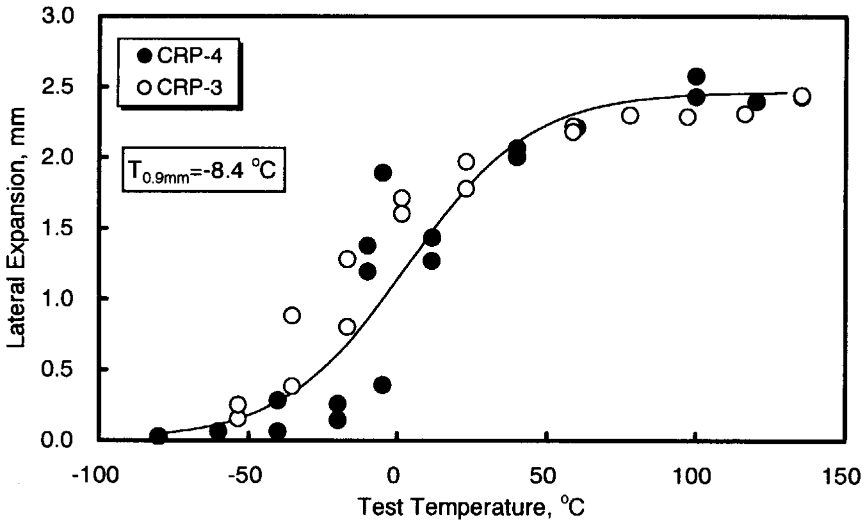
Table 4--Comparison of indexing temperatures in the transition range of materials before neutron irradiation. unit: °C

	T_{28J}	T_{41J}	T_{68J}	$T_{0\ PCCv}$	(average)	T_{0_1TCT}
JRQ	-37	-25	-6	-66 -65*	-65	-66*
Steel A	-54	-42	-23	-70 -82	-76	-67
Steel B	-68	-61	-50	-84 -111	-98	-97

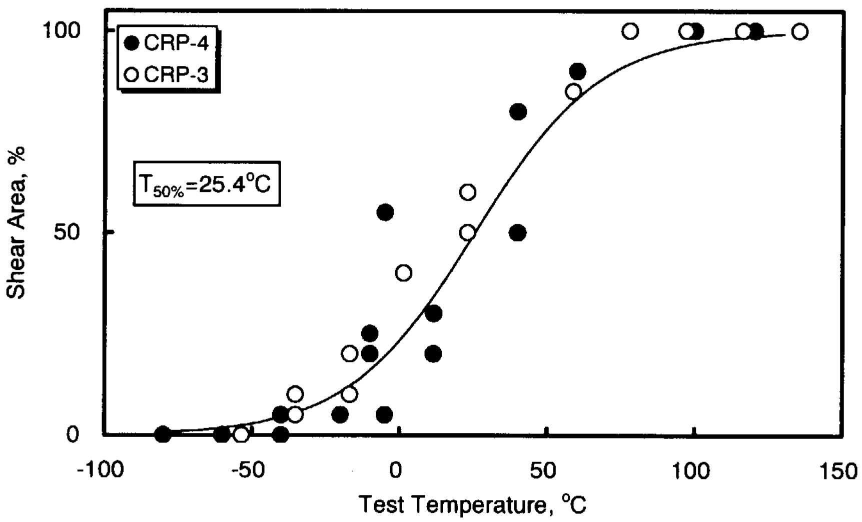
*: The other block for CRP-3 was used for the specimen.



(a) Absorbed energy

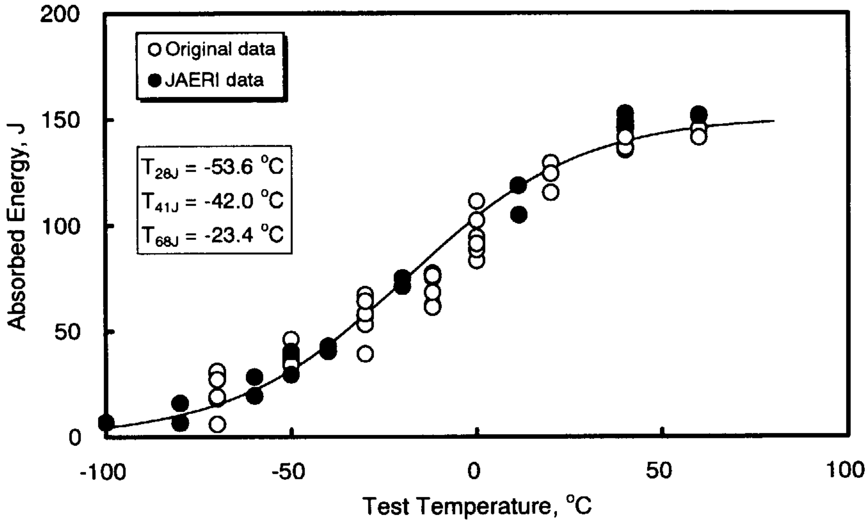


(b) Lateral expansion

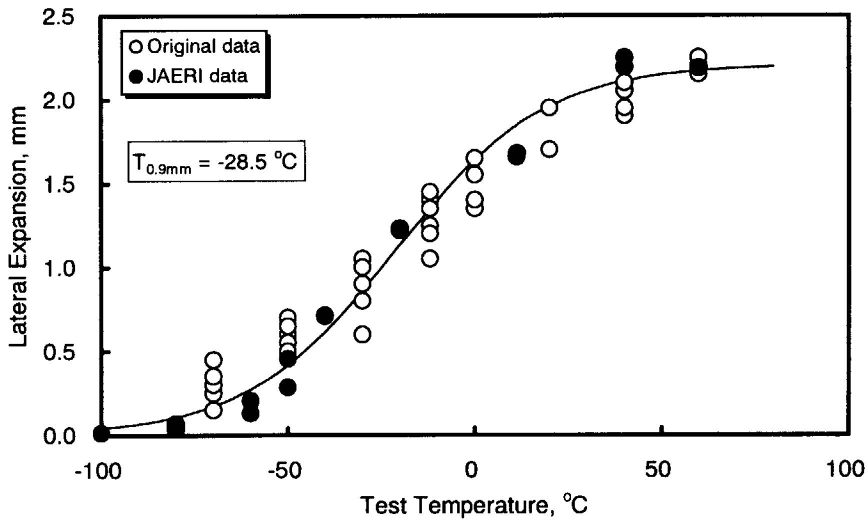


(c) Shear area

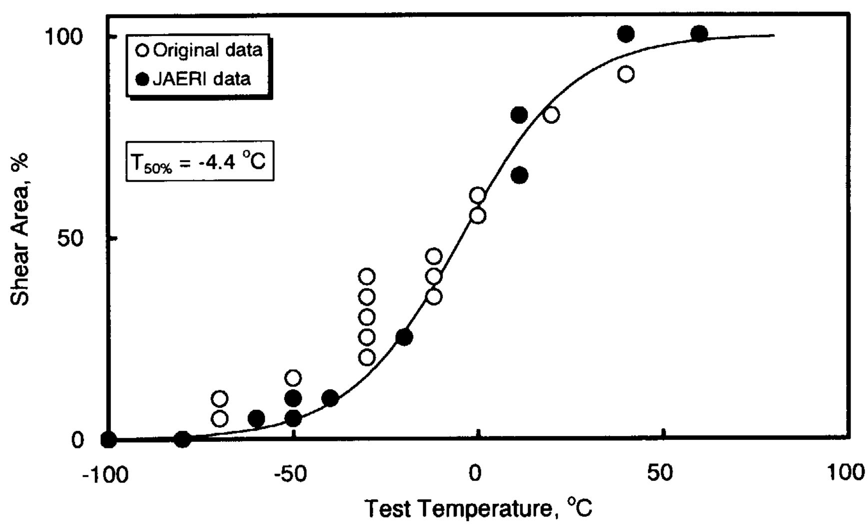
Figure 3—Charpy impact test results for JRQ before irradiation.



(a) Absorbed energy

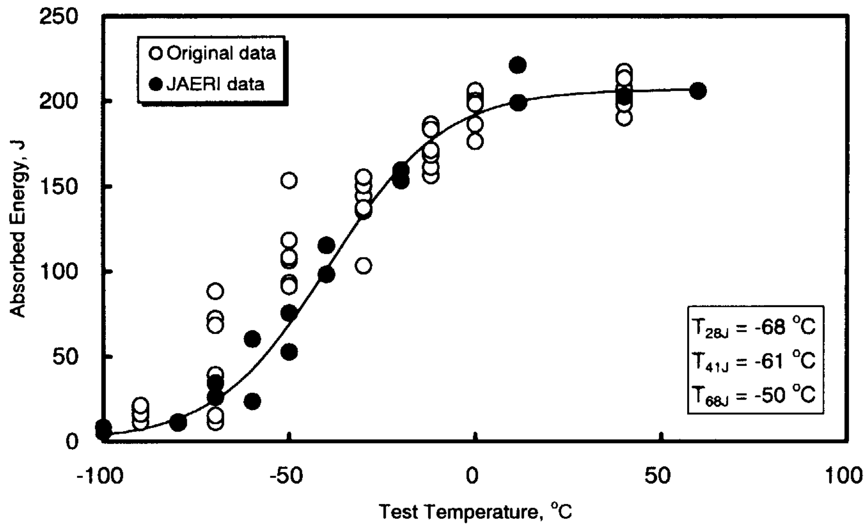


(b) Lateral expansion

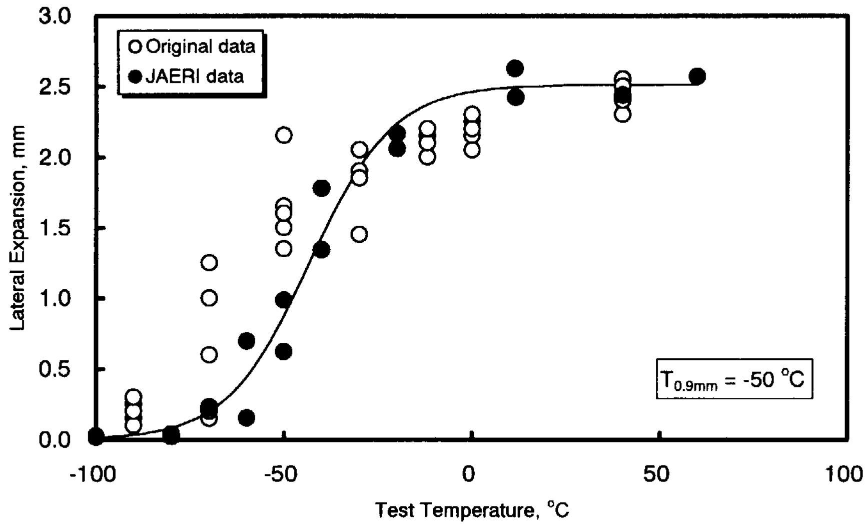


(c) Shear area

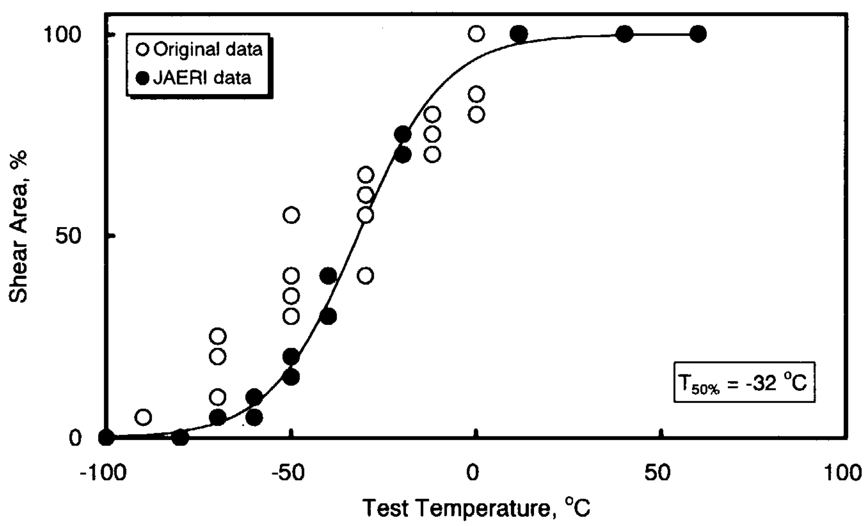
Figure 4—Charpy impact test results for Steel A before irradiation.



(a) Absorbed energy

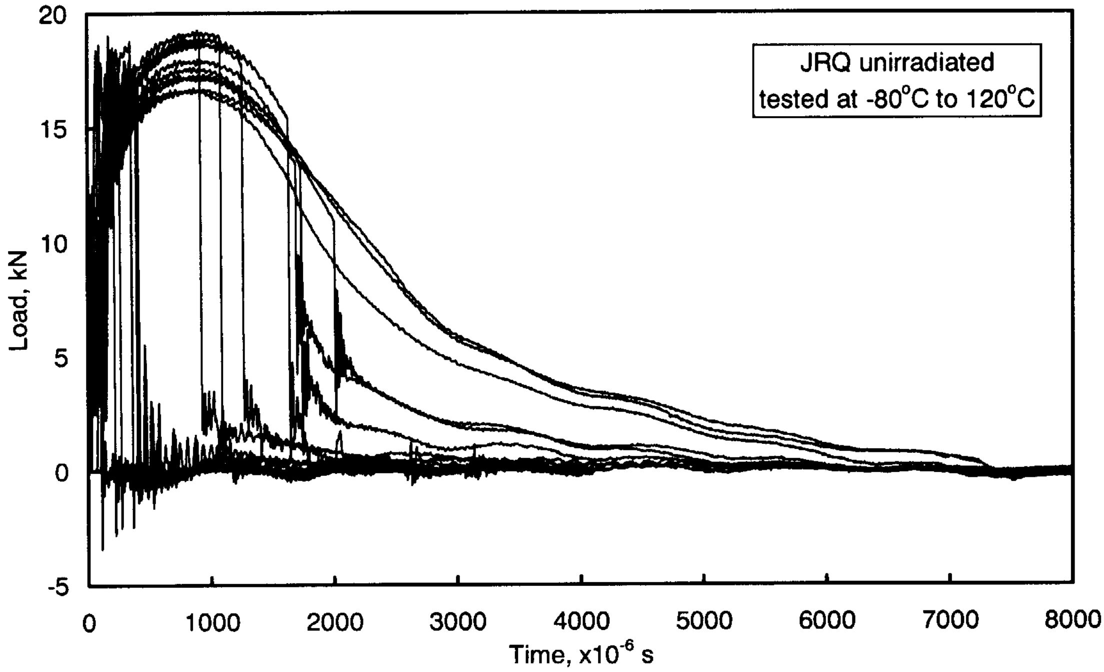


(b) Lateral expansion

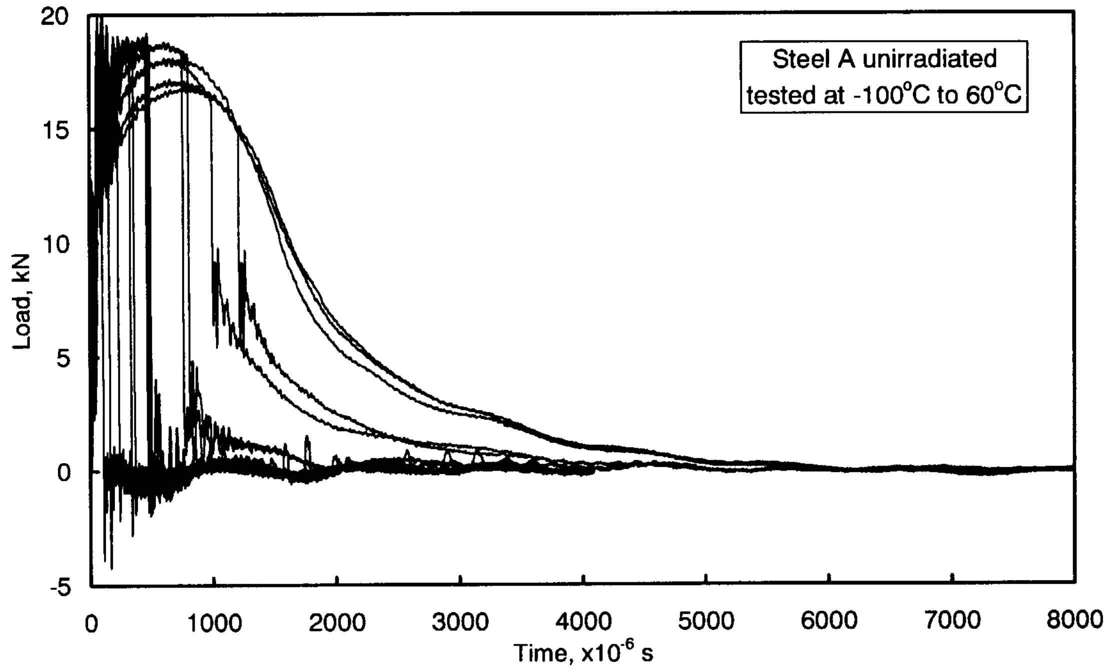


(c) Shear area

Figure 5—Charpy impact test results for Steel B before irradiation.

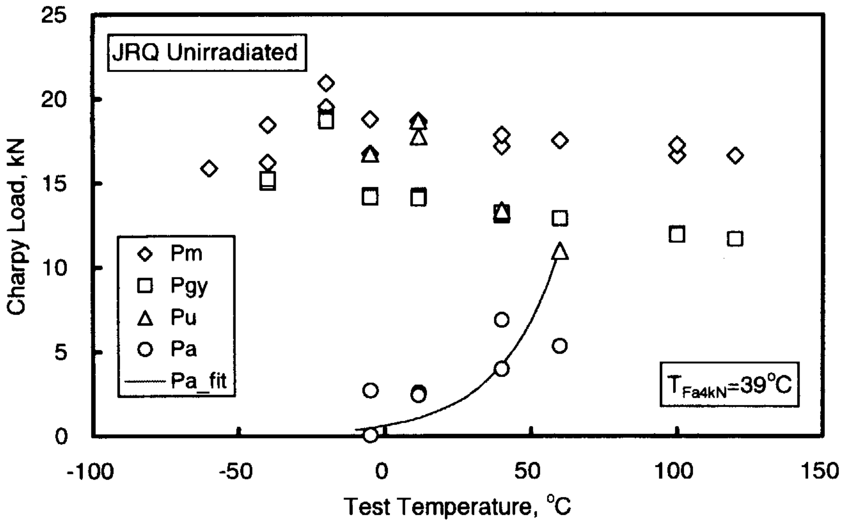


(a) JRQ unirradiated

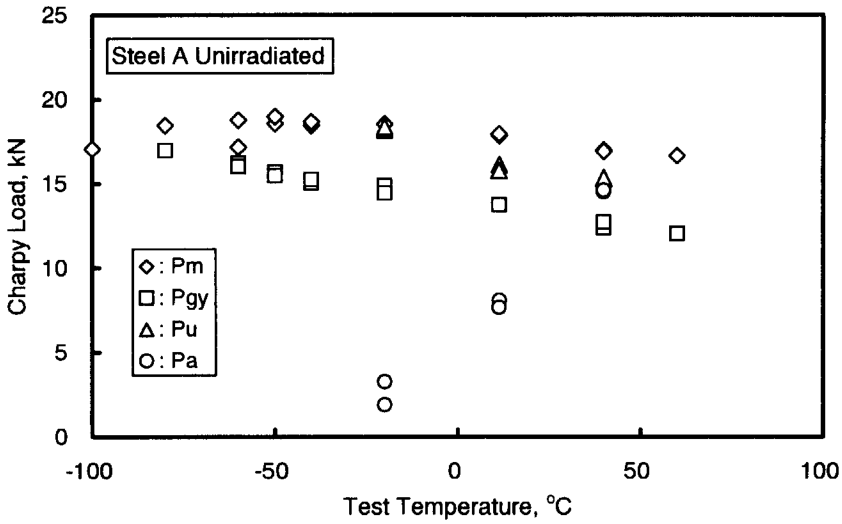


(b) Steel A unirradiated

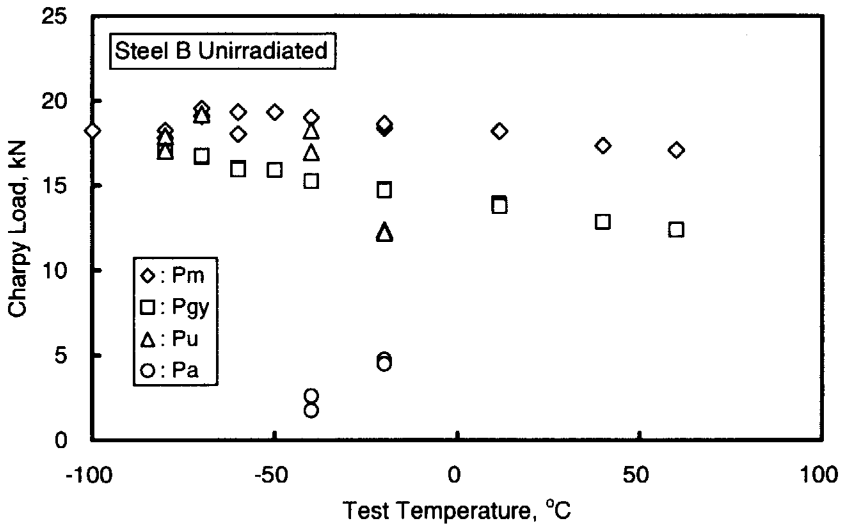
Figure 6---Load-time signals obtained from instrumented Charpy impact tests.



(a) JRQ.

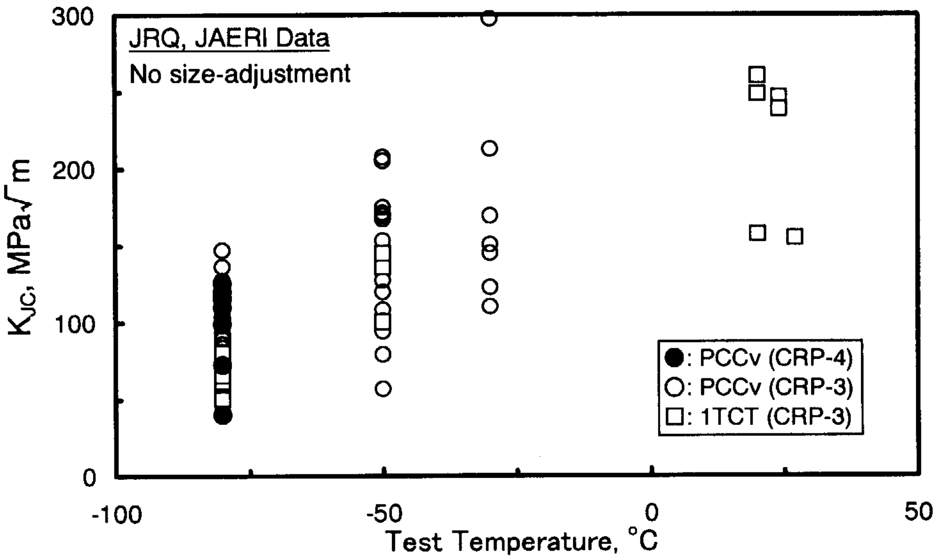


(b) Steel A

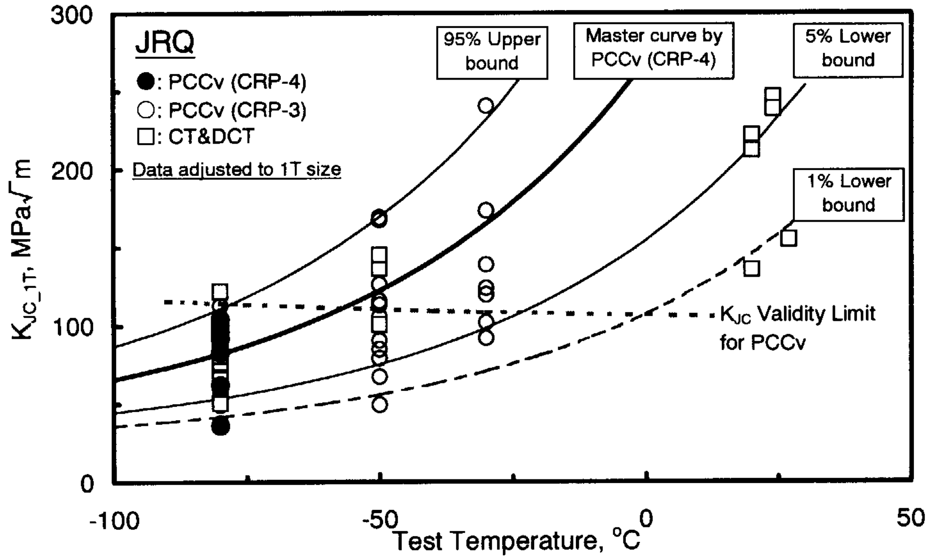


(c) Steel B

Figure 7—Charpy load diagrams for materials used.

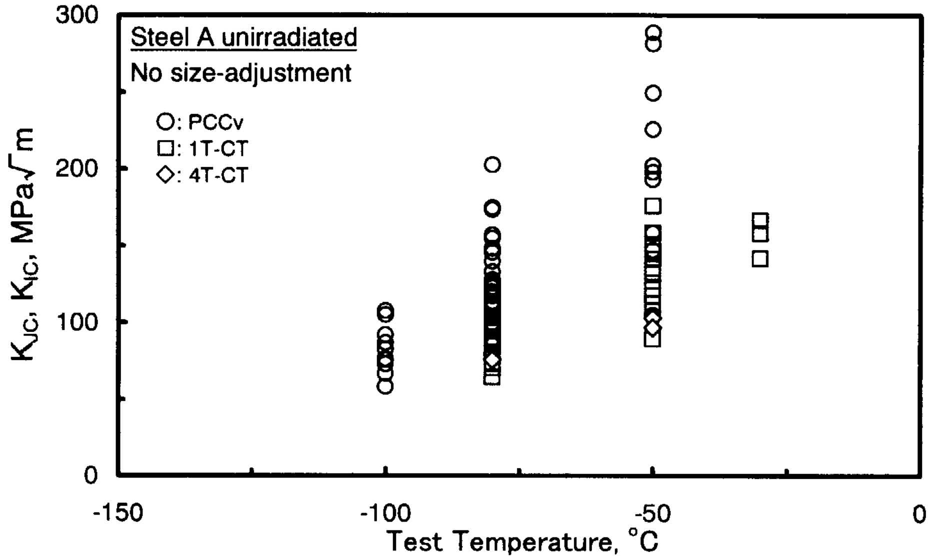


(a) K_{JC} values according to ASTM E1921.

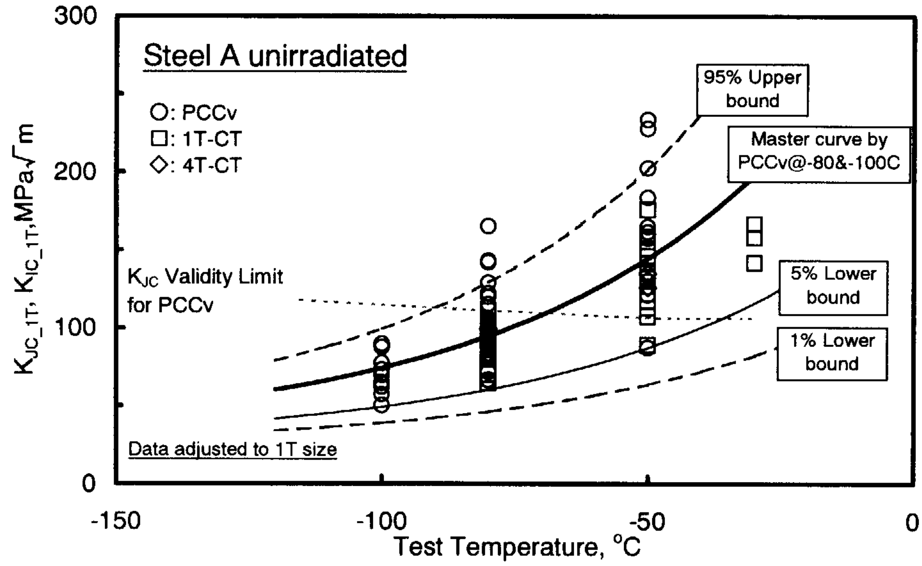


(b) Size adjusted K_{JC} values and master curve

Figure 8—Fracture toughness test results for JRQ.

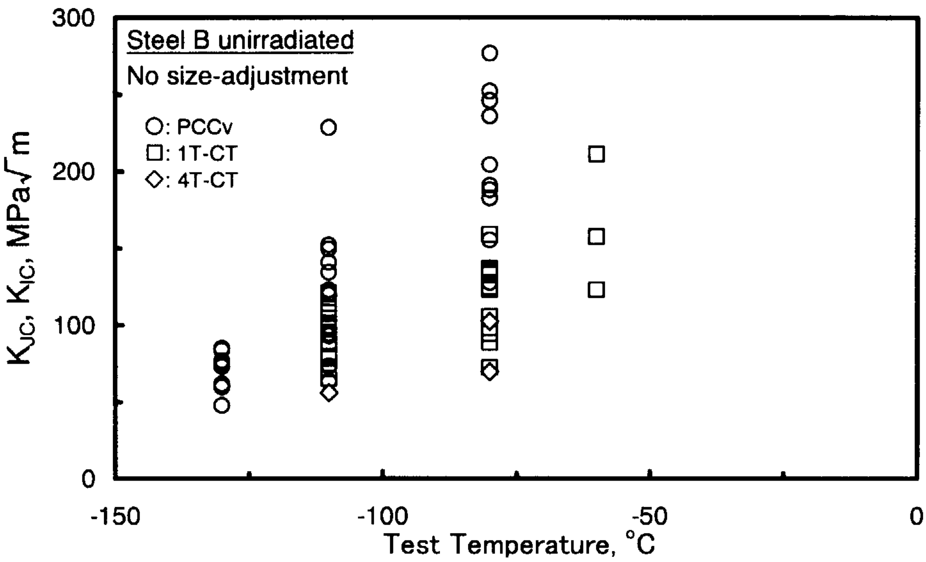


(a) K_{JC} values according to ASTM E1921.

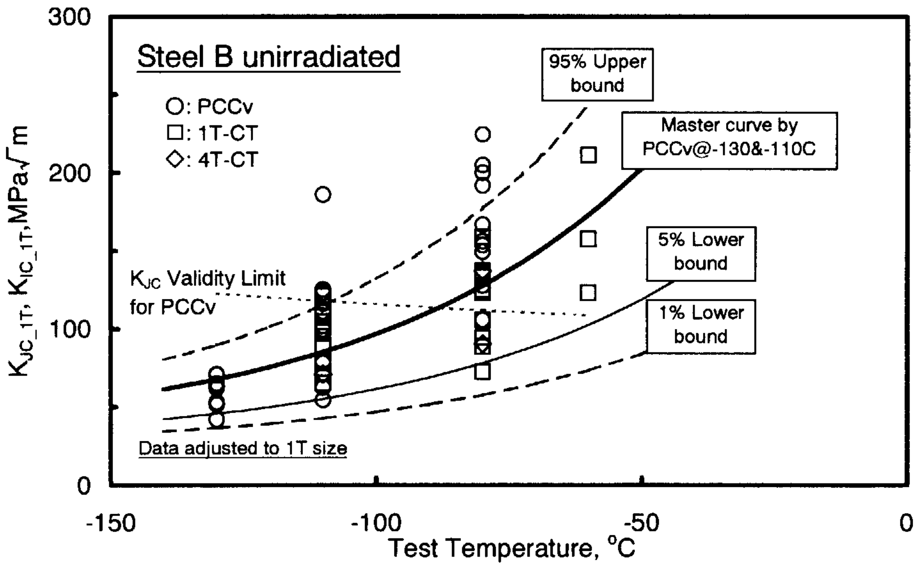


(b) Size adjusted K_{JC} values and master curve

Figure 9—Fracture toughness test results for Steel A.

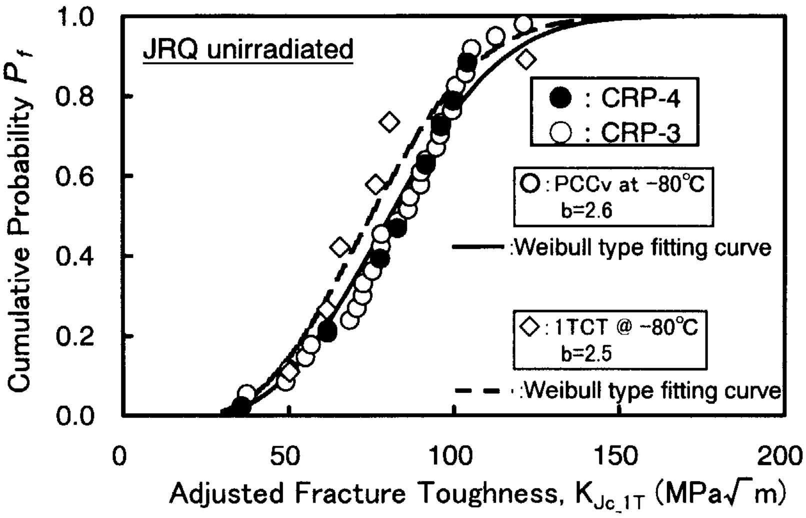


(a) K_{JC} values according to ASTM E1921.

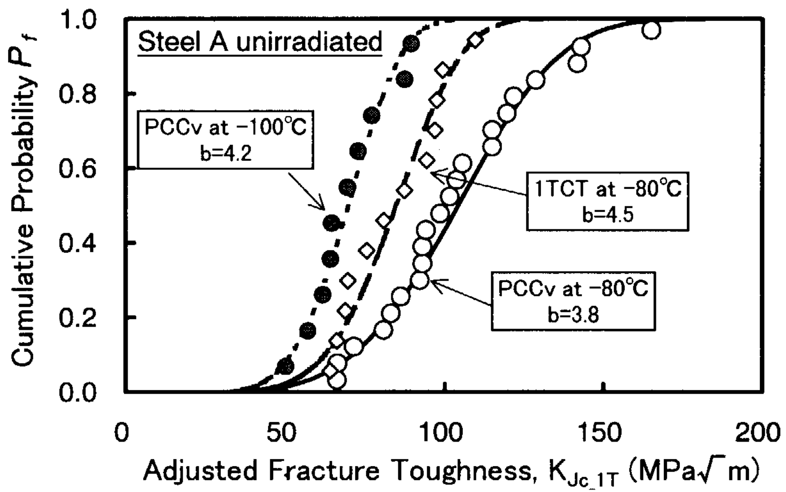


(b) Size adjusted K_{JC} values and master curve

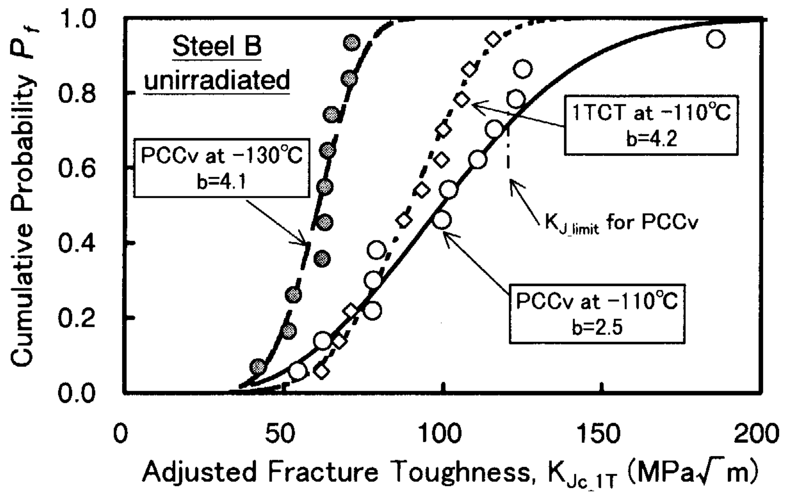
Figure 10—Fracture toughness test results for Steel B.



(a) Unirradiated JRQ tested at -80°C.



(b) Unirradiated Steel A tested at –100°C and -80°C.



(c) Unirradiated Steel B tested at –130°C and -110°C.

Figure 11--Weibull plot of fracture toughness data from 1T-CT and PCCv.

6. Optional Part

6.1 Reactor and Capsule for Neutron Irradiation

Irradiation for JRQ specimens was performed using two capsules at JMTR. The irradiation capsule contains electric heaters, thermocouples and fluence monitors as well as some kinds of test specimens. The capsules were irradiated at the irradiation hole in the second Beryllium reflector region of the JMTR core. Figure 12 shows the geometry of irradiation capsules. Figure 13 shows the core configuration of JMTR and the irradiation positions for the capsule Nos. 1 and 2.

The target values of fast neutron fluence are $2.5x10^{19}$ n/cm^2 (E>1MeV) for the capsule No.1 and $9x10^{19}$ n/cm^2 (E>1MeV) for the capsule No.2. The neutron flux is approximately $1.3x10^{13}$ n/cm^{2}s (E>1MeV) for both capsules. The fast and thermal neutron fluences at each specimen position are evaluated by the activity measurements of several fluence monitors in the capsule and the calculation based on the effective cross section of reaction. The fluence monitors are pure Fe and Al-Co for fast and thermal neutrons, respectively. The temperature of specimens in the capsules during irradiation was controlled at 290°C by several electric heaters.

Figure 14 shows temperature histories measured by thermocouples (TC) in the capsule No. 1 during neutron irradiation at JMTR. The TC No. 1 indicated about 300°C because it was located in SS308 specimens for another purpose. The readout from TC No.10 was very low temperature due to its wrong position. The other TCs showed 281°C to 292°C.

Irradiation for specimens of Steel A and Steel B was also performed at JMTR in the other project(1). The target neutron fluence was $10x10^{19}$ n/cm^2 (E>1MeV) for specimens of both steels. The design and the other conditions of capsules for both steels are the same as those for JRQ.

Neutron fluence value and dpa for each specimen is calculated based on the activity measurements of fluence monitors and a series of calculation. The average values of fast neutron fluence for each material are about $2.5x10^{19}$, $13x10^{19}$ and $11x10^{19}$ n/cm^2 for JRQ, Steel A and Steel B, respectively.

6.2 Specimen

Test specimens encapsulated were tensile bar, Charpy-V impact, pre-cracked Charpy, sub-size Charpy and round bar for non-destructive measurement. Charpy-V and precracked Charpy specimens were arranged to the same neutron flux positions in the capsule. Figure 12 indicates the positions of specimens in the capsule.

6.3 Results of Post-irradiation Tests

6.3.1 Charpy Impact Test

Figure 15 shows Charpy impact test results together with tanh-fitted transition curves before and after irradiation. Test results of irradiated specimens for each material are listed in Attachment. Transition temperatures at 28J, 41J and 68J (T_{28J}, T_{41J} and T_{68J}) for each material are also indicated in the figure. The T_{28J} temperatures are 43, 101 and 2°C for JRQ, Steel A and Steel B, respectively. The shifts of Charpy 41J transition temperature are 80, 155 and 71°C for JRQ, Steel A and Steel B, respectively.

6.3.2 Fracture Toughness Test

Based on the results of Charpy impact tests for irradiated specimens, a test temperature for irradiated precracked Charpy specimens was selected. The recommended temperature for precracked Charpy specimens in ASTM E1921 is 50°C lower than T_{28J}. Therefore, we selected 0°C, 50°C and -50°C as the primary test temperatures for irradiated PCCv specimens of JRQ, Steel A and Steel B, respectively.

Figure 16 shows the effect of irradiation on the fracture toughness of three materials. Based on the E1921, the T_0 value after irradiation was determined by the data sets at a single test temperature. The T_0 values for JRQ, Steel A and Steel B are 9°C, 72°C and -25°C, respectively. Master curves before and after irradiation were also indicated in the figure together with 5% and 95% tolerance bounds. The shifts of T_0 are 76°C, 148°C and 73°C, for JRQ, Steel A and Steel B, respectively. When the T_0 shifts are compared with the Charpy T_{41J} shifts, those are almost equivalent.

However, the highest datum of Steel A after irradiation was significantly higher than the other data although that datum was still valid. When the highest datum is excepted from the data set, the T_0 moves to higher temperature by about 30°C, as shown in Figure 16 (b) by dotted lines. After the exception of the highest point, the rest of data were fitted well in the tolerance bounds of 5% and 95%. Although this exception is not a standard practice, it may be considered as the treatment of an outlier and leads to a conservative estimation.

For the rest of irradiated PCCv specimens, higher test temperature was selected to see the temperature dependence. For JRQ, the secondary temperature of 25°C was chosen. Results are shown in Figure 16(a). All six data are valid. The T_0 temperature from this set of tests is 38°C according to ASTM E1921. The shift of T_0 temperature due to neutron irradiation is 104°C. For these specimens, it must be noted that the average neutron fluence is 2.9×10^{19} n/cm^2, which was ~20% higher than those for the first set of PCCv specimens and Charpy impact specimens. The 20% difference in fast neutron fluence, however, results in only less than 10% difference in Charpy transition temperature shift according to the prediction formula[e.g.13]. Since the measured Charpy shift was 80°C, the T_0 shift of 104°C from the second set is much higher than the Charpy shift for the equivalent irradiation condition. For the multi-temperature test results, further analysis is necessary, such as the T_0 determination method, the shape change of master curve.

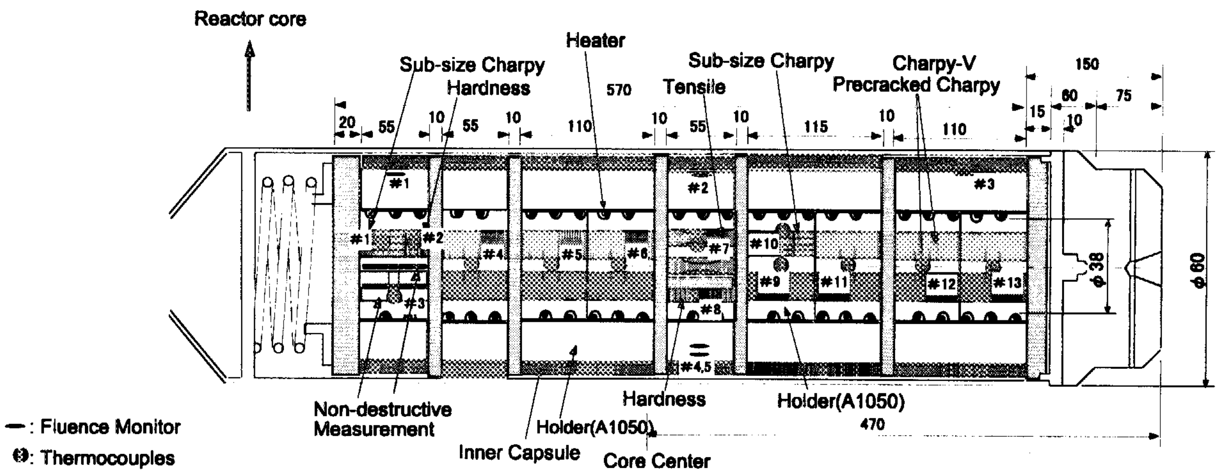


Figure 12--General view of JMTR irradiation capsule.

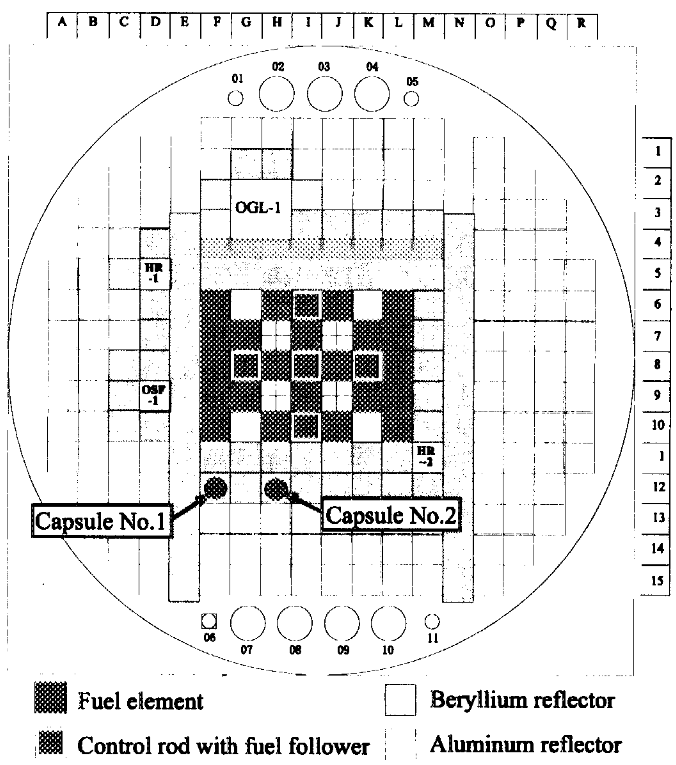


Figure 13—Core configuration of JMTR and irradiation positions for the capsule Nos. 1 and 2.

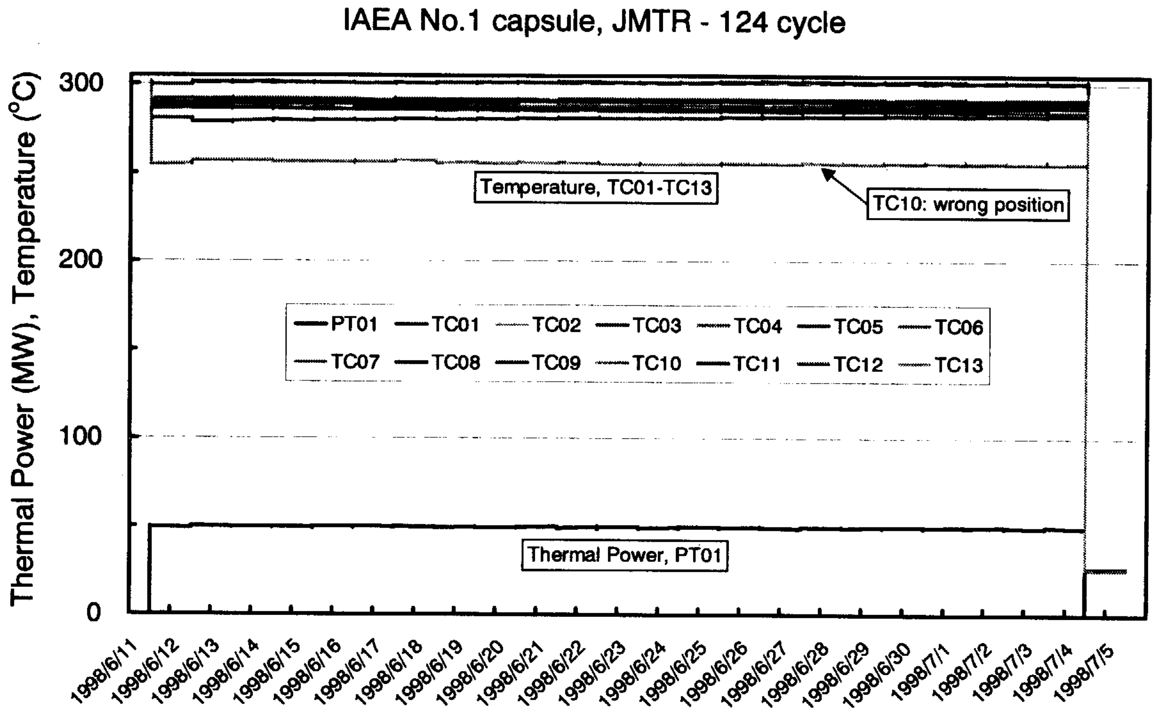
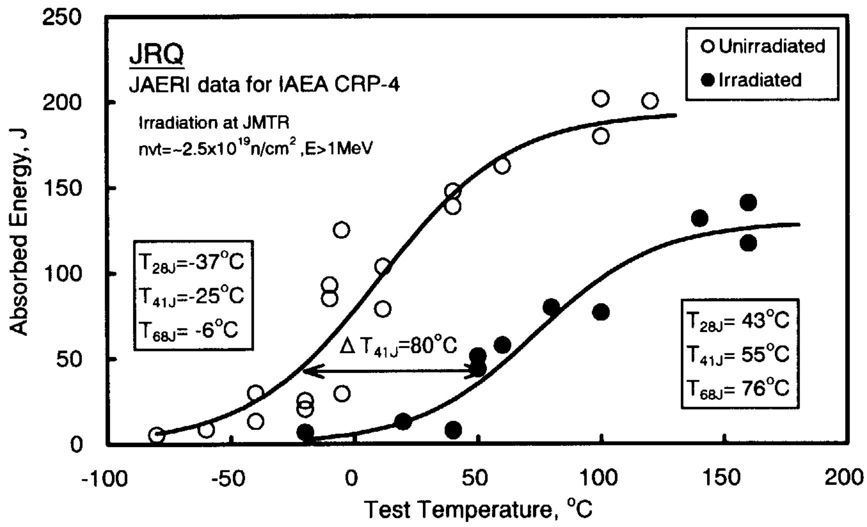
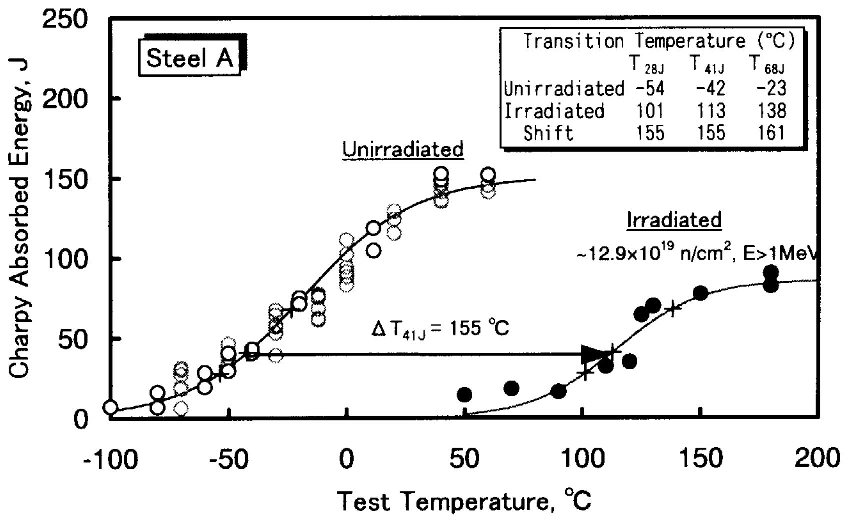


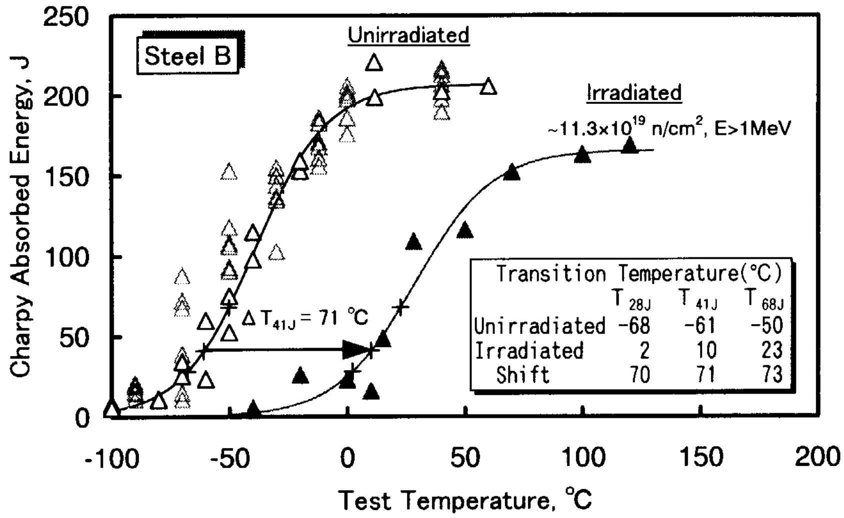
Figure 14--Temperature history during JMTR irradiation of IAEA No. 1 capsule.



(a) JRQ

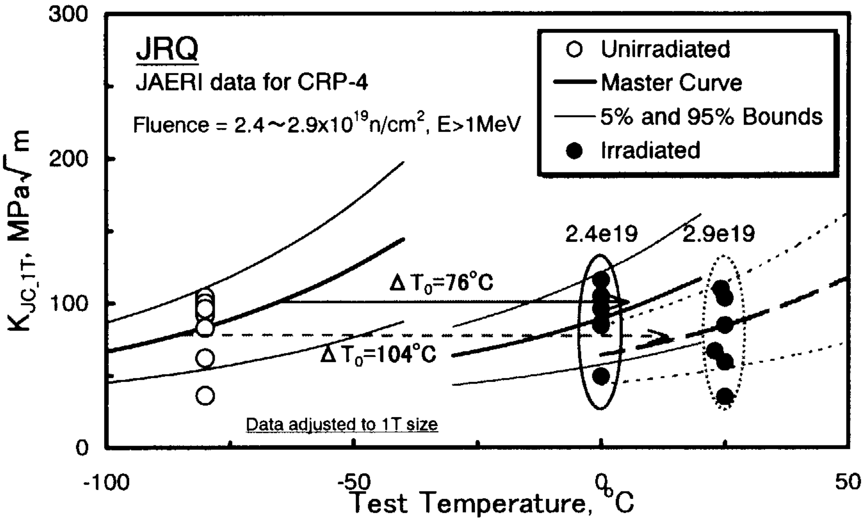


(b) Steel A

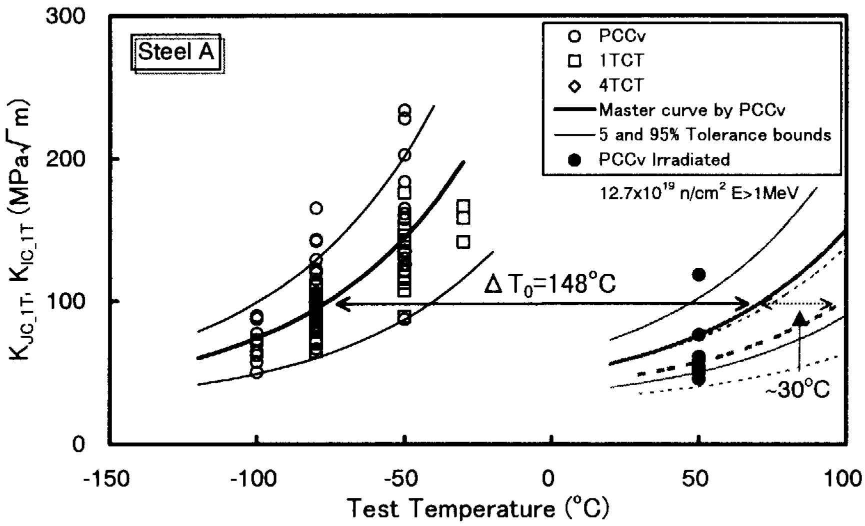


(c) Steel B

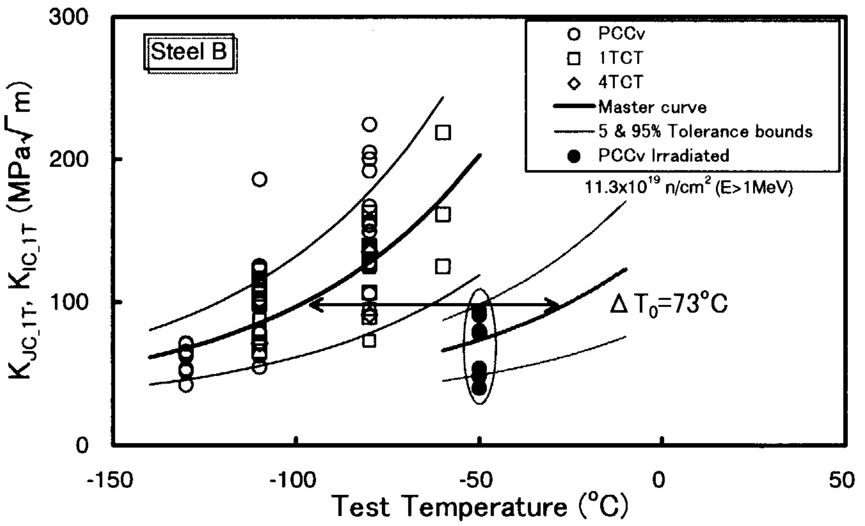
Figure 15—Charpy transition curves before and after neutron irradiation.



(a) JRQ



(b) Steel A



(c) Steel B

Figure 16—Fracture toughness data before and after irradiation and the master curves.

7. Summary and Conclusions

According to the Research Agreement No. 9736 between the IAEA and the JAERI, we have performed the test program for the IAEA CRP-IV on "Assuring Structural Integrity of Reactor Pressure Vessels" at JAERI. JAERI received the IAEA reference material JRQ from the IAEA CRP coordinator in June 1997. The test program has been conducted using the JRQ block and additional materials from our own program.

For a mandatory part of the program, instrumented Charpy impact tests and fracture toughness tests using precracked Charpy specimens were performed and reported here. As an optional part, neutron irradiation to specimens of JRQ was conducted at JMTR. Post-irradiation tests were performed at Research Hot Laboratory of JAERI. In this report, the results of irradiated Charpy and PCCv specimens of JRQ from capsule No.1 as well as those of Steel A and Steel B were described. Additional tests for irradiated specimens and other optional tests will be performed in the near future. Conclusions obtained up to now are as follows.

(1) the data form Charpy impact and fracture toughness tests of JRQ agreed well with the data in the CRP-3,

(2) the scatter of fracture toughness of JRQ is relatively large, i. e., the Weibull slope "b" is less than 3,

(3) the reference temperature T_0 from PCCv is in good agreement with T_0 from 1TCT when the tests are performed at the recommended temperature or the data has no invalid data,

(4) the T_0 after neutron irradiation was determined by testing six to eight specimens at the recommended temperature,

(5) the relation between the shifts of T_0 and Charpy transition temperature was almost equivalent but significantly affected by the treatment of highest datum and testing temperature, and

(6) further studies on the fracture toughness evaluation are necessary; such as the treatment of outlier, temperature dependence after irradiation, multi-temperature analysis and so on.

Acknowledgment

The part of this work has been carried out under the contract between JAERI and the Science and Technology Agency of Japan under the auspices of the special account law for electric power development promotion. The irradiation and post-irradiation testing were performed at the Department of JMTR at Oarai Research Establishment and Research Hot Laboratory at Tokai Research Establishment, respectively.

References

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(2) JIS B7722, "Charpy impact testing machines," Japanese Industry Standard, Japanese Standards Association, 1990.

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(12) H. Viehrig and J. Boehmert, "Some Issues by Using the Master Curve Concept," Transactions of the 15th International Conference on Structural Mechanics in Reactor Technology, Seoul, Korea, August 15-20, 1999.

(13) U. S. NRC, Regulatory Guide 1.99, Revision 2, "Radiation Embrittlement of Reactor Vessel Materials," May 1988.

Attachments

NOTCH IMPACT TESTING

ORGANIZATION	Japan Atomic Energy Research Institute
MATERIAL TYPE	A533B class 1 plate
MATERIAL ID.	5 JRQ 43
SPECIMENS ORIENTATION (ASTM)	T-L
SPECIMENS DEPTH [mm]	1xx, 6xx: 52 mm, 2xx, 5xx: 65 mm 3xx, 4xx: 78 mm
TESTING STANDARD: ASTM / ISO	ISO
SPECIMENS SIZE [mm]	10 x 10 x 55

SPECIMENS ID.	TESTING TEMPERATURE [C]	ABSORBED ENERGY, KCV [J]	LATERAL EXPANSION [mm]	SHEAR FRACTURE [%]
Q112	-80	5.2	0.023	0
Q212	-60	8.3	0.059	0
Q172	-40	13.1	0.060	0
Q142	-40	29.5	0.279	5
Q441	-20	20.2	0.142	5
Q431	-20	25.1	0.254	5
Q572	-10	84.8	1.376	20
Q542	-10	92.8	1.190	25
Q272	-5	29.3	0.389	5
Q242	-5	125	1.890	55
Q421	11.5	78.7	1.267	20
Q411	11.6	103.5	1.434	30
Q512	40	138.6	2.063	50
Q312	40	147.3	2.005	80
Q451	60	162.2	2.210	90
Q342	100	179.4	2.431	100
Q461	100	201.4	2.577	100
Q372	120	199.8	2.395	100

$$\mathbf{KCV = A + B \cdot tgh\,[\,(T - T_0)\,/\,C\,]}$$

A	B	C	T_0
96.8	96.8	52.9	10.3

NOTCH IMPACT TESTING

ORGANIZATION	Japan Atomic Energy Research Institute
MATERIAL TYPE	A533B class 1 plate
MATERIAL ID.	Steel A
SPECIMENS ORIENTATION (ASTM)	T-L
SPECIMENS DEPTH [mm]	57
TESTING STANDARD: ASTM / ISO	ISO
SPECIMENS SIZE [mm]	10 x 10 x 55

SPECIMENS ID.	TESTING TEMPERATURE [C]	ABSORBED ENERGY, KCV [J]	LATERAL EXPANSION [mm]	SHEAR FRACTURE [%]
AV13	-100	6.9	0.010	0
AV14	-80	15.9	0.067	0
AV15	-80	6.5	0.036	0
AV32	-60	19.2	0.129	5
AV18	-60	28.2	0.202	5
AV33	-50	29.3	0.284	5
AV34	-50	40.3	0.456	10
AV16	-40	40.3	0.715	10
AV17	-40	42.7	0.708	10
AV11	-20	74.9	1.233	25
AV12	-20	70.9	1.220	25
AV20	11.3	118.4	1.657	80
AV19	11.4	104.4	1.677	65
AV35	40	148.4	2.248	100
AV36	40	152.2	2.193	100
AV37	60	151.6	2.187	100

$$\mathbf{KCV = A + B \cdot tgh\,[\,(T - T_0)\,/\,C\,]}$$

A	B	C	T_0
75.4	75.4	47.1	-18.8

NOTCH IMPACT TESTING

ORGANIZATION	Japan Atomic Energy Research Institute
MATERIAL TYPE	A533B class 1 plate
MATERIAL ID.	Steel B
SPECIMENS ORIENTATION (ASTM)	T-L
SPECIMENS DEPTH [mm]	57
TESTING STANDARD: ASTM / ISO	ISO
SPECIMENS SIZE [mm]	10 x 10 x 55

SPECIMENS ID.	TESTING TEMPERATURE [C]	ABSORBED ENERGY, KCV [J]	LATERAL EXPANSION [mm]	SHEAR FRACTURE [%]
BV13	-100	8.0	0.027	0
BV14	-100	5.6	0.016	0
BV15	-80	11.2	0.022	0
BV16	-80	10.6	0.040	0
BV36	-70	25.7	0.233	5
BV37	-70	34.2	0.224	5
BV32	-60	59.9	0.697	10
BV33	-60	23.4	0.152	5
BV34	-50	52.5	0.623	15
BV35	-50	75.2	0.985	20
BV17	-40	97.9	1.343	30
BV18	-40	114.9	1.778	40
BV11	-20	153.0	2.059	70
BV12	-20	159.0	2.165	75
BV20	11.4	220.9	2.625	100
BV19	11.6	198.8	2.421	100
BV38	40	202.5	2.437	100
BV39	60	205.6	2.568	100

$$\mathbf{KCV = A + B \bullet tgh\left[(T - T_0) / C \right]}$$

A	B	C	T_0
103.5	103.5	30.7	-39.3

STATIC FRACTURE TOUGHNESS TESTING

ORGANIZATION	Japan Atomic Energy Research Institute
MATERIAL TYPE	A533B class 1 Plate
MATERIAL ID.	5 JRQ 43
SPECIMEN ORIENTATION (ASTM)	T-L
SPECIMENS DEPTH [mm]	1xx, 6xx: 52 mm, 2xx, 5xx: 65 mm 3xx, 4xx: 78 mm
TESTING STANDARD	ASTM E813, E1921
TESTING RATE (Crosshead Speed)	0.2 mm/min
SPECIMENS SIZE [mm] THICKNESS [mm] / WIDTH [mm] / SIDE GROOVE [%]	Precracked Charpy 10 mm / 10 mm 20% (10 % each side)

SPECIMENS ID.	TESTING TEMPERATURE [C]	CRACK SIZE [mm]	Δa [mm]	K_{IC} [$MPa.m^{0.5}$]	K_{JC} [$MPa.m^{0.5}$] (E1921)	K_{JC_1T} [$MPa.m^{0.5}$]
Q241	-80	5.06	-	-	39.9	35.8
Q511	-80	4.97	-	-	72.6	61.8
Q211	-80	4.93	-	-	99.0	82.8
Q171	-80	4.95	-	-	110.0	91.5
Q271	-80	5.07	-	-	115.7	96.1
Q141	-80	4.96	-	-	120.3	99.7
Q111	-80	5.01	-	-	125.6	104.0
Q541	-80	4.90	-	-	92.6	77.7

T_{28J} [°C]	T_0 [°C]
-36.7	-65.8

$$K_{JC} = A + B \bullet \exp(C . T)$$

A	B	C

STATIC FRACTURE TOUGHNESS TESTING

ORGANIZATION	Japan Atomic Energy Research Institute
MATERIAL TYPE	A533B class 1 Plate
MATERIAL ID.	JRQ for CRP-3
SPECIMEN ORIENTATION (ASTM)	T-L
SPECIMENS DEPTH [mm]	63 mm
TESTING STANDARD	ASTM E813, E1921
TESTING RATE (Crosshead Speed)	0.5 mm/min
SPECIMENS SIZE [mm] THICKNESS [mm] / WIDTH [mm] / SIDE GROOVE [%]	1T-CT 25 mm / 50 mm 20% (10 % each side)

SPECIMENS ID.	TESTING TEMPERATURE [C]	CRACK SIZE [mm]	Δa [mm]	K_{IC} [MPa.m$^{0.5}$]	K_{JC} [MPa.m$^{0.5}$] (E1921)	K_{JC_1T} [MPa.m$^{0.5}$]
JA-RQ4	-80	25.635	-	-	50.2	
JA-RQ10	-80	25.628	-	-	61.6	
JA-RQ6	-80	25.673	-	-	65.5	
JA-RQ3	-80	25.418	-	-	76.3	
JA-RQ2	-80	25.59	-	-	80.5	
JA-RQ9	-80	25.565	-	-	121.8	
JA-RQ5	-50	25.582	-	-	136.2	
JA-RQ7	-50	25.474	-	-	100.4	
JA-RQ8	-50	25.313			145.0	

T_{28J} [°C]	T_0 [°C]
-36.7	-66.4

$$K_{JC} = A + B \bullet \exp(C \cdot T)$$

A	B	C

STATIC FRACTURE TOUGHNESS TESTING

ORGANIZATION	Japan Atomic Energy Research Institute
MATERIAL TYPE	A533B class 1 Plate
MATERIAL ID.	Steel A
SPECIMEN ORIENTATION (ASTM)	T-L
SPECIMENS DEPTH [mm]	57 mm
TESTING STANDARD	ASTM E813, E1921
TESTING RATE(Crosshead Speed)	0.2 mm/min
SPECIMENS SIZE [mm] THICKNESS [mm] / WIDTH [mm] / SIDE GROOVE [%]	Precracked Charpy 10 mm / 10 mm (Span: 40 mm) 20% (10 % each side)

SPECIMEN ID.	TESTING TEMPERATURE [C]	CRACK SIZE [mm]	Δa [mm]	K_{IC} [MPa.m$^{0.5}$]	K_{JC} [MPa.m$^{0.5}$] (E1921)	K_{JC_1T} [MPa.m$^{0.5}$]
AP347	-100	5.114	-	-	57.9	50.1
AP354	-100	5.047	-	-	66.7	57.2
AP350	-100	4.984	-	-	72.7	61.9
AP349	-100	5.152	-	-	75.6	64.3
AP352	-100	5.054	-	-	76.2	64.7
AP348	-100	4.977	-	-	82.4	69.7
AP346	-100	5.330	-	-	86.5	72.9
AP353	-100	4.998	-	-	91.9	77.2
AP351	-100	5.089	-	-	104.9	87.5
AP355	-100	5.019	-	-	107.5	89.6
AP115	-80	5.094	-	-	78.3	66.4
AP356	-80	4.956	-	-	78.5	66.5
AP30	-80	5.017	-	-	85.0	71.7
AP122	-80	5.116	-	-	96.6	81.0
AP123	-80	5.097	-	-	99.5	83.3
AP38	-80	5.071	-	-	103.5	86.4
AP315	-80	5.000	-	-	110.8	92.3
AP360	-80	4.977	-	-	111.9	93.1
AP124	-80	5.183	-	-	112.0	93.2
AP323	-80	5.016	-	-	113.3	94.2
AP316	-80	5.068	-	-	118.8	98.7
AP121	-80	5.082	-	-	122.6	101.7
AP307	-80	5.039	-	-	125.3	103.8

AP119	-80	5.210	-	-	127.7	105.7
AP357	-80	5.158	-	-	139.6	115.1
AP114	-80	5.149	-	-	139.6	115.1
AP301	-80	5.126	-	-	145.3	119.7
AP358	-80	5.159	-	-	148.1	121.9
AP120	-80	5.253	-	-	156.9	128.9
AP359	-80	5.011	-	-	173.1	141.8
AP125	-80	5.132	-	-	174.7	143.0
AP116	-80	5.143	-	-	202.3	165.0

Note: Yield Strength: 586 MPa (–100°C), 550 MPa (–80°C)

T_0 from 1TCT: -66.9°C

T_{28J} [°C]	$T_{0@-80°C}$ [°C]	$T_{0@-100°C}$ [°C]
-53.6	-82.3	-69.6

STATIC FRACTURE TOUGHNESS TESTING

ORGANIZATION	Japan Atomic Energy Research Institute
MATERIAL TYPE	A533B class 1 Plate
MATERIAL ID.	Steel B
SPECIMEN ORIENTATION (ASTM)	T-L
SPECIMENS DEPTH [mm]	57 mm
TESTING STANDARD	ASTM E813, E1921
TESTING RATE(Crosshead Speed)	0.2 mm/min
SPECIMENS SIZE [mm] THICKNESS [mm] / WIDTH [mm] / SIDE GROOVE [%]	Precracked Charpy 10 mm / 10 mm (Span: 40 mm) 20% (10 % each side)

SPECIMEN ID.	TESTING TEMPERATURE [C]	CRACK SIZE [mm]	Δa [mm]	K_{IC} [MPa.m$^{0.5}$]	K_{JC} [MPa.m$^{0.5}$] (E1921)	K_{JC_1T} [MPa.m$^{0.5}$]
BP30	-130	4.980	-	-	72.8	62.0
BP417	-130	5.036	-	-	61.5	53.0
BP418	-130	4.868	-	-	84.2	71.1
BP419	-130	4.848	-	-	74.0	62.9
BP420	-130	4.799	-	-	47.5	41.9
BP421	-130	4.847	-	-	59.5	51.4
BP422	-130	4.974	-	-	76.5	64.9
BP423	-130	4.809	-	-	83.5	70.5
BP424	-130	4.874	-	-	74.0	62.9
BP425	-130	4.846	-	-	75.0	63.7
BP119	-110	5.007	-	-	63.2	54.4
BP29	-110	5.071	-	-	73.2	62.3
BP124	-110	5.116	-	-	92.7	77.9
BP120	-110	5.145	-	-	93.1	78.2
BP127	-110	5.232	-	-	94.2	79.1
BP123	-110	5.130	-	-	119.9	99.5
BP121	-110	5.177	-	-	122.6	101.6
BP39	-110	4.959	-	-	134.2	110.8
BP126	-110	5.069	-	-	140.8	116.1
BP117	-110	5.082	-	-	149.4	122.9
BP118	-110	5.250	-	-	152.0	125.0
BP115	-110	5.302	-	-	228.3	185.7

Note: Yield Strength = 675 MPa (–130°C), 620 MPa (–110°C)

T_0 from 1TCT: -97.4°C

T_{28J} [°C]	**$T_{0@-130°C}$ [°C]**	**$T_{0@-110°C}$ [°C]**
-68.6	-84.2	-111.0

NOTCH IMPACT TESTING

ORGANIZATION	Japan Atomic Energy Research Institute
MATERIAL TYPE	A533B class 1 plate
MATERIAL ID.	5JRQ43 Irradiated at JMTR
SPECIMENS ORIENTATION (ASTM)	T-L
SPECIMENS DEPTH [mm]	1xx, 6xx: 52 mm, 2xx, 5xx: 65 mm 3xx, 4xx: 78 mm
TESTING STANDARD: ASTM / ISO	ISO
SPECIMENS SIZE [mm]	10 x 10 x 55

SPECIMEN ID.	FLUENCE (E>1MeV) [n/cm^2]	IRRADIATION TEMPERATURE [C]	TESTING TEMPERATURE [C]	ABSORBED ENERGY, KCV [J]	LATERAL EXPANSION [mm]	SHEAR FRACTURE [%]
Q522	2.06E+19	292	-20	6.7	0.214	0
Q122	2.00E+19	291	19.6	12.7	0.276	7
Q222	2.51E+19	290	40	8.0	0.220	9
Q352	2.37E+19	287	40	7.3	0.260	10
Q552	2.41E+19	292	50	51.0	0.898	26
Q582	1.98E+19	288	50	43.7	0.797	25
Q152	2.35E+19	291	60	57.4	1.013	27
Q282	2.43E+19	291	80	79.5	1.283	45
Q382	2.78E+19	287	100	76.6	1.501	56
Q182	2.26E+19	288	140	131.2	2.052	100
Q252	2.65E+19	288	160	140.6	2.146	100
Q322	2.84E+19	291	160	116.8	1.857	100

$$\mathbf{KCV = A + B \cdot tgh\left[\,(T - T_0)\,/\,C\,\right]}$$

A	B	C	T_0
64.8	64.8	48.5	73.8

NOTCH IMPACT TESTING

ORGANIZATION	Japan Atomic Energy Research Institute
MATERIAL TYPE	A533B class 1 plate
MATERIAL ID.	Steel A Irradiated at JMTR
SPECIMENS ORIENTATION (ASTM)	T-L
SPECIMENS DEPTH [mm]	57
TESTING STANDARD: ASTM / ISO	ISO
SPECIMENS SIZE [mm]	10 x 10 x 55

SPECIMEN ID.	FLUENCE (E>1MeV) [n/cm^2]	IRRADIATION TEMPERATURE [C]	TESTING TEMPERATURE [C]	ABSORBED ENERGY, KCV [J]	LATERAL EXPANSION [mm]	SHEAR FRACTURE [%]
AV22	1.12E+20	289	50	14.0	0.195	7
AV29	1.43E+20	285	70	18.1	0.494	11
AV26	1.27E+20	289	90	16.0	0.419	22
AV28	1.22E+20	285	110	32.0	0.584	24
AV27	1.49E+20	289	120	34.8	0.656	37
AV23	1.32E+20	289	125	64.2	1.213	71
AV24	1.22E+20	284	130	69.7	1.426	82
AV31	1.31E+20	290	150	77.3	1.445	82
AV30	1.11E+20	290	180	82.1	1.468	100
AV25	1.43E+20	284	180	90.1	1.711	100

$$\mathbf{KCV = A + B \bullet tgh\,[\,(T - T_0) / C\,]}$$

A	B	C	T_0
43.0	43.0	35.8	114.4

NOTCH IMPACT TESTING

ORGANIZATION	Japan Atomic Energy Research Institute
MATERIAL TYPE	A533B class 1 plate
MATERIAL ID.	Steel B Irradiated at JMTR
SPECIMENS ORIENTATION (ASTM)	T-L
SPECIMENS DEPTH [mm]	57
TESTING STANDARD: ASTM / ISO	ISO
SPECIMENS SIZE [mm]	10 x 10 x 55

SPECIMEN ID.	FLUENCE (E>1MeV) [n/cm^2]	IRRADIATION TEMPERATURE [C]	TESTING TEMPERATURE [C]	ABSORBED ENERGY, KCV [J]	LATERAL EXPANSION [mm]	SHEAR FRACTURE [%]
BV23	1.07E+20	289	-40	5.3	0.091	2
BV26	1.30E+20	290	-20	25.9	0.431	7
BV25	1.11E+20	290	0	22.9	0.437	18
BV28	1.24E+20	290	10	16.0	0.347	14
BV22	1.17E+20	290	15	48.7	0.825	31
BV21	9.94E+19	290	28.2	108.9	1.590	54
BV27	1.06E+20	290	50	116.2	1.779	67
BV30	1.13E+20	283	70	152.3	2.195	84
BV24	1.26E+20	289	100	163.2	2.285	100
BV29	9.61E+19	283	120	168.7	2.342	100

$$\mathbf{KCV = A + B \bullet tgh\,[\,(T - T_0)\,/\,C\,]}$$

A	B	C	T_0
83.0	83.0	33.2	28.6

STATIC FRACTURE TOUGHNESS TESTING

ORGANIZATION	Japan Atomic Energy Research Institute
MATERIAL TYPE	A533B class 1 Plate
MATERIAL ID.	5JRQ43 Irradiated at JMTR
SPECIMEN ORIENTATION (ASTM)	T-L
SPECIMENS DEPTH [mm]	1xx, 6xx: 52 mm, 2xx, 5xx: 65 mm 3xx, 4xx: 78 mm
TESTING STANDARD	ASTM E813, E1921
TESTING RATE(Crosshead Speed)	0.2 mm/min
SPECIMENS SIZE [mm] THICKNESS [mm] / WIDTH [mm] / SIDE GROOVE [%]	Precracked Charpy 10 mm / 10 mm (Span: 40 mm) 20% (10 % each side)

SPECIMEN ID.	FLUENCE (E>1MeV) [n/cm^2]	IRRADIATION TEMPERATURE [C]	TESTING TEMPERATURE [C]	CRACK SIZE [mm]	Δa [mm]	K_{JC} (E1921) [MPa.m$^{0.5}$]	K_{JC_1T} [MPa.m$^{0.5}$]
Q581	2.12E+19	288	0	5.174	-	56.4	49.0
Q471	2.70E+19	290	0	4.874	-	100.5	84.1
Q521	2.21E+19	292	0	5.077	-	101.5	84.8
Q181	2.43E+19	288	0	5.028	-	102.3	85.5
Q281	2.60E+19	291	0	5.112	-	115.2	95.7
Q351	2.55E+19	287	0	5.090	-	126.4	104.7
Q121	2.15E+19	291	0	5.139	-	140.2	115.6
Q151	2.52E+19	291	24.2	5.030	-	132.8	109.7
Q251	2.84E+19	288	25	5.022	-	38.8	35.0
Q321	3.05E+19	291	25	5.010	-	101.2	84.6
Q381	2.98E+19	287	25	4.964	-	124.6	103.2
Q481	3.16E+19	290	23	4.970	-	78.5	66.5
Q551	2.59E+19	292	25	5.046	-	69.1	59.1

Note: Yield Strength = 648 MPa at 0°C, 612 MPa at 25°C

T_{28J} [°C]	$T_{0@0°C}$ [°C]	$T_{0@25°C}$ [°C]
42.5	8.8	38

STATIC FRACTURE TOUGHNESS TESTING

ORGANIZATION	Japan Atomic Energy Research Institute
MATERIAL TYPE	A533B class 1 Plate
MATERIAL ID.	Steel A Irradiated at JMTR
SPECIMEN ORIENTATION (ASTM)	T-L
SPECIMENS DEPTH [mm]	57 mm
TESTING STANDARD	ASTM E813, E1921
TESTING RATE(Crosshead Speed)	0.2 mm/min
SPECIMENS SIZE [mm] THICKNESS [mm] / WIDTH [mm] / SIDE GROOVE [%]	Precracked Charpy 10 mm / 10 mm (Span: 40 mm) 20% (10 % each side)

SPECIMEN ID.	FLUENCE (E>1MeV) [n/cm^2]	IRRADIATION TEMPERATURE [C]	TESTING TEMPERATURE [C]	CRACK SIZE [mm]	Δa [mm]	K_{JC} (E1921) [MPa.m$^{0.5}$]	K_{JC_1T} [MPa.m$^{0.5}$]
AP27	1.27E+20	285	50	5.206	-	52.1	45.5
AP29	1.26E+20	285	50	5.125	-	57.4	49.7
AP34	1.21E+20	285	50	5.046	-	60.2	52.0
AP35	1.43E+20	285	50	5.072	-	62.5	53.8
AP37	1.30E+20	290	50	5.020	-	68.5	58.6
AP24	1.32E+20	289	50	5.114	-	71.7	61.1
AP25	1.21E+20	284	50	5.091	-	90.9	76.3
AP22	1.16E+20	290	50	5.121	-	143.8	118.4

Note: Yield Strength at 50°C = 684.5 MPa

T_{28J} [°C]	T_0 [°C]
101.4	71.6 (95.6)*

*: T_0 except for AP22

STATIC FRACTURE TOUGHNESS TESTING

ORGANIZATION	Japan Atomic Energy Research Institute
MATERIAL TYPE	A533B class 1 Plate
MATERIAL ID.	Steel B Irradiated at JMTR
SPECIMEN ORIENTATION (ASTM)	T-L
SPECIMENS DEPTH [mm]	57 mm
TESTING STANDARD	ASTM E813, E1921
TESTING RATE(Crosshead Speed)	0.2 mm/min
SPECIMENS SIZE [mm] THICKNESS [mm] / WIDTH [mm] / SIDE GROOVE [%]	Precracked Charpy 10 mm / 10 mm (Span: 40 mm) 20% (10 % each side)

SPECIMEN ID.	FLUENCE (E>1MeV) [n/cm^2]	IRRADIATION TEMPERATURE [C]	TESTING TEMPERATURE [C]	CRACK SIZE [mm]	Δa [mm]	K_{JC} (E1921) [MPa.m$^{0.5}$]	K_{JC_1T} [MPa.m$^{0.5}$]
BP33	1.12E+20	290	-50	5.040	-	44.8	39.7
BP27	1.11E+20	284	-50	4.964	-	55.2	48.0
BP31	1.12E+20	284	-50	4.910	-	61.9	53.3
BP26	1.28E+20	289	-50	5.096	-	92.8	77.9
BP35	1.07E+20	290	-50	5.102	-	94.6	79.3
BP24	1.18E+20	290	-50	5.063	-	108.7	90.5
BP21	1.04E+20	290	-50	5.037	-	112.2	93.3

Note: Yield Strength at -50°C = ~650 MPa

T_{28J} [°C]	T_0 [°C]
2.2	-25.0

国際単位系（SI）と換算表

表1　SI基本単位および補助単位

量	名称	記号
長さ	メートル	m
質量	キログラム	kg
時間	秒	s
電流	アンペア	A
熱力学温度	ケルビン	K
物質量	モル	mol
光度	カンデラ	cd
平面角	ラジアン	rad
立体角	ステラジアン	sr

表2　SIと併用される単位

名称	記号
分, 時, 日	min, h, d
度, 分, 秒	°, ′, ″
リットル	l, L
トン	t
電子ボルト	eV
原子質量単位	u

1 eV=1.60218×10^{-19}J
1 u=1.66054×10^{-27}kg

表3　固有の名称をもつSI組立単位

量	名称	記号	他のSI単位による表現
周波数	ヘルツ	Hz	s^{-1}
力	ニュートン	N	$m\cdot kg/s^2$
圧力，応力	パスカル	Pa	N/m^2
エネルギー,仕事,熱量	ジュール	J	N·m
工率，放射束	ワット	W	J/s
電気量，電荷	クーロン	C	A·s
電位，電圧，起電力	ボルト	V	W/A
静電容量	ファラド	F	C/V
電気抵抗	オーム	Ω	V/A
コンダクタンス	ジーメンス	S	A/V
磁束	ウェーバ	Wb	V·s
磁束密度	テスラ	T	Wb/m^2
インダクタンス	ヘンリー	H	Wb/A
セルシウス温度	セルシウス度	℃	
光束	ルーメン	lm	cd·sr
照度	ルクス	lx	lm/m^2
放射能	ベクレル	Bq	s^{-1}
吸収線量	グレイ	Gy	J/kg
線量当量	シーベルト	Sv	J/kg

表4　SIと共に暫定的に維持される単位

名称	記号
オングストローム	Å
バーン	b
バール	bar
ガル	Gal
キュリー	Ci
レントゲン	R
ラド	rad
レム	rem

1 Å=0.1nm=10^{-10}m
1 b=100fm²=$10^{-28}m^2$
1 bar=0.1MPa=10^5Pa
1 Gal=1cm/s²=$10^{-2}m/s^2$
1 Ci=3.7×10^{10}Bq
1 R=2.58×10^{-4}C/kg
1 rad=1cGy=10^{-2}Gy
1 rem=1cSv=10^{-2}Sv

表5　SI接頭語

倍数	接頭語	記号
10^{18}	エクサ	E
10^{15}	ペタ	P
10^{12}	テラ	T
10^{9}	ギガ	G
10^{6}	メガ	M
10^{3}	キロ	k
10^{2}	ヘクト	h
10^{1}	デカ	da
10^{-1}	デシ	d
10^{-2}	センチ	c
10^{-3}	ミリ	m
10^{-6}	マイクロ	μ
10^{-9}	ナノ	n
10^{-12}	ピコ	p
10^{-15}	フェムト	f
10^{-18}	アト	a

（注）

1．表1－5は「国際単位系」第5版，国際度量衡局1985年刊行による。ただし，1 eVおよび1 uの値はCODATAの1986年推奨値によった。
2．表4には海里，ノット，アール，ヘクタールも含まれているが日常の単位なのでここでは省略した。
3．barは，JISでは流体の圧力を表わす場合に限り表2のカテゴリーに分類されている。
4．EC閣僚理事会指令ではbar，barnおよび「血圧の単位」mmHgを表2のカテゴリーに入れている。

換算表

力	N(=10^5dyn)	kgf	lbf
	1	0.101972	0.224809
	9.80665	1	2.20462
	4.44822	0.453592	1

粘度　1 Pa·s(N·s/m²)=10 P(ポアズ)(g/(cm·s))

動粘度　1m²/s=10^4St(ストークス)(cm²/s)

圧力	MPa(=10bar)	kgf/cm²	atm	mmHg(Torr)	lbf/in²(psi)
	1	10.1972	9.86923	7.50062×10^{3}	145.038
	0.0980665	1	0.967841	735.559	14.2233
	0.101325	1.03323	1	760	14.6959
	1.33322×10^{-4}	1.35951×10^{-3}	1.31579×10^{-3}	1	1.93368×10^{-2}
	6.89476×10^{-3}	7.03070×10^{-2}	6.80460×10^{-2}	51.7149	1

エネルギー・仕事・熱量	J(=10^7 erg)	kgf·m	kW·h	cal(計量法)	Btu	ft·lbf	eV
	1	0.101972	2.77778×10^{-7}	0.238889	9.47813×10^{-4}	0.737562	6.24150×10^{18}
	9.80665	1	2.72407×10^{-6}	2.34270	9.29487×10^{-3}	7.23301	6.12082×10^{19}
	3.6×10^{6}	3.67098×10^{5}	1	8.59999×10^{5}	3412.13	2.65522×10^{6}	2.24694×10^{25}
	4.18605	0.426858	1.16279×10^{-6}	1	3.96759×10^{-3}	3.08747	2.61272×10^{19}
	1055.06	107.586	2.93072×10^{-4}	252.042	1	778.172	6.58515×10^{21}
	1.35582	0.138255	3.76616×10^{-7}	0.323890	1.28506×10^{-3}	1	8.46233×10^{18}
	1.60218×10^{-19}	1.63377×10^{-20}	4.45050×10^{-26}	3.82743×10^{-20}	1.51857×10^{-22}	1.18171×10^{-19}	1

1 cal＝4.18605J（計量法）
＝4.184J（熱化学）
＝4.1855J（15℃）
＝4.1868J（国際蒸気表）

仕事率　1 PS(仏馬力)
＝75 kgf·m/s
＝735.499W

放射能	Bq	Ci
	1	2.70270×10^{-11}
	3.7×10^{10}	1

吸収線量	Gy	rad
	1	100
	0.01	1

照射線量	C/kg	R
	1	3876
	2.58×10^{-4}	1

線量当量	Sv	rem
	1	100
	0.01	1

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