Transactions, SMiRT 16, Washington DC, August 2001 *Paper # 1308*

Lifetime Management Study of RPV for Qinshan NPP Phase I

QU Jiadi[1)], HE Yinbiao[1)], LI Hua[2)], CHEN Fuquan[1)]

1)Shanghai Nuclear Engineering Research & Design Institute, No.29 Hong Cao Rd., P.R. China, 200233
2)Qinshan NPP Phase I

ABSTRACT

Qinshan NPP Phase I is the first NPP in China, and it was mainly designed by Chinese own efforts. From a prototype point of view, this paper presents the research on both prophase management of lifetime and operation-feedback for the RPV extending structural integrity ensuring of the RPV under design conditions to structural integrity considerations for the RPV under operation conditions, aging mechanism and aging management scheme. Furthermore, a preliminary analysis is carried out using some operation data.

INTRODUCTION

Qinshan Phase I 300MWe NPP, which is the first NPP in China, has been in commissioning operation since 1990. As a prototype reactor, it is necessary to conduct prophase management of lifetime to accumulate integrated information of the key components. Then, we can launch operation-feedback study to obtain the exact quantitative value of the real safety margin. Prophase management of the key components includes design analysis, material, manufacture, test, transportation, keeping and installation. Of these, the central segment is comprehensive analysis which aim at ensuring structural integrity of the key components under design conditions, i.e. covering the accumulated impact due to various severe conditions suffered in the rest of lifetime with sufficient conservatism of design conditions. At the same time, material lower limit, combined with degradation and damage, which are caused in the course of manufacture, test, transportation and installation, are taken into account. Meanwhile, the operation-feedback study aims at ensuring structure integrity of the RPV under operation conditions through lifetime management of material aging and component degradation. It is also verification for the prediction. The real conservative margin can be given through monitoring.

For RPV, to ensure its structure integrity in design, it mainly depends on establishing an integrated ensuring system including rule system, material limit system, loading system, comprehensive analysis and evaluation system. There are four categories of factors that reflect and affect the structural integrity of RPV in operation. They are radiation category (e.g., radiation inspection test and brittleness evaluation, neutron fluency tracing calculation, etc.), fatigue category (e.g., thermal and mechanical fatigue), fracture category (e.g. damage accumulating defect and PTS) and corrosion category (e.g. interface stress corrosion, erosion and cladding map cracking).

STRUCTURAL INTEGRITY ENSURING FOR THE RPV OF QINSHAN NPP PHASE I

Integrity Conception and Logical System

To carry out such a mechanical analysis aiming at ensuring the structural integrity of the RPV, the primary consideration is to form a logically complete general guideline and to establish a concept of integrity on the basis of a thorough study on a rule system, loading system and analysis system. And then, in order to obtain a proper conservative margin for the analysis, some site-measurements shall be performed, making the engineering and the research aspects depend on each other. Thus, a logical system of research--analysis, site measurement –software, calculation, which takes the rule system, the loading system and the analysis system as its main contents, is then completed.

To ensure structural integrity, an integrity conception has to be formed. That means, integral and essential ensuring, for example, material, weld, test and environmental influence, is a prerequisite for comprehensive and complete performance. For mechanical analysis, the so-called integrity at least includes following four items, i.e. operation condition and load combination, structure and interface, functional failure criteria, stress limits. These four items shall be all integrated. It is not self-evident to form integral conception. In practice, there are instances of engineering accidents happened due to unintegral structure, unintegral conditions, unintegral basis failure form, unintegral interface or unintegral testing environment in component analysis. The logical development of forming the guideline of "obtaining concrete evidence and holding conservative margin" in design cycle is operation-feedback study. Consequently, design, operation and management can be organically united. Because of the sufficient information of the fundamental test and analysis, the operation-feedback study is to be of great technical significance with forming independent technique accumulation.

Evaluation System

For the design of the key components of the PWR NPP, there are many types of regulations and codes. But as far as the evaluation systems are concerned, there are mainly French regulation and American ASME Code. The former evaluates vessels according to ultimate load-bearing capacity; the latter gives value limits according to stress classification and safety factor. Although both them use the method of design by analysis. The latter is simpler and more convenient. Therefore, even AFCEN, which consists of EDF and Framatome, adopts ASME evaluation system. But, no matter French RCC-M, Japanese JIS or British Code, they all absorb the idea of design by analysis and then developed their native foundation research. For example, RCC-M Appendix ZG, Rapid Fracture Analysis, JIS ΔRT_{NDT} equation and doubling plant lifetime, and in order to improve the PFM method, Japan developed PFM Code, Korea considers establishing its own PTS evaluation criteria, etc. All these progress with quite big step are achieved by establishing equations and curves on the basis of their native test data.

Loading Consideration

The design transients comprise system operation conditions and design basis accidents. It is just a reference enveloped load mode. The current transient stress analysis for the RPV is neither an analysis of the real stress nor a probabilistic stress analysis. It is a boundary limit analysis of uncertain conservative margin with some optional range in processing loading. The design is required to give conservative evaluation. The design transients use three types of internationally popular PWR transients for reference, which have become contrast bases. While the further consideration of mechanical analysis direct towards accurate monitoring of operation through which the conservative margin is obtained. For this reason, the site-measurement were carried out to obtain concrete evidence and then consider implementing operation transient monitoring to determine the site-measured load spectra.

From the loading analysis we know, besides pressure-temperature transient loading, there are three other loading conditions with uncertainties, including bolt loading, nozzle loading, and temperature loading (induced by heat transfer coefficient and thermal material properties). For the RPV of Qinshan NPP Phase I, a sealing analysis code has been developed during the stage of design. It solves bolt loading, which belongs to covariant loading, through the covariant deformation of the bolt-flange joint. The solved bolt loading has to be confirmed by testing and analyzing. And then the hot loading increment of the bolt would be measured at during the NPP's commissioning under hot condition. At last, a conclusion of 30% hot increment of bolts can be obtained. In addition, the heat transfer coefficients have been deduced in the hot sealing test. This method can be originally generalized to the site. We consider producing a lot of important technical data during the hot test and measuring the testing transients with sufficient monitoring points to obtain the site-measured testing loading spectra and then the operation loading spectra. The nozzle loading including support loading of the RPV shall be confirmed by site measurement.

In order to obtain the fundus information about transient stress analyses, the site ultrasonic measurement of the welding residual stresses of the circular weldseam of the RPV of PC NPP was preformed before and after the hydrostatic test.

Rule System Considerations

The systematic aging management course advocated by IAEA includes the content, which embodied as documentary regular requirements, safety criteria and documents about relevant activities, of coordinating activities of aging management. National codes, standards, design specifications and final safety review plan constitute a logical system of rules which is of integrity, consistency and grade. China has not established its own rule system on aging management. The reference [13] is the equivalent citation or general reference for vessel.

FATIGUE ANALYSIS DISCUSSION AND SIMPLIFIED FATIGUE ESTIMATION

Fatigue Analysis Discussion

The all-around fatigue analysis deals with many pair of data and heavy and complicated calculations. It involves all the cycle loading, all the locations and all the time history. It is known from the analysis of cyclic operation in ASME Code III NB-222.4 that if there are two or more types of stress cycle, the cumulative effect and mutual influence shall be taken in to account. The procedures are as follows. Designate the specified number of cycles for each type of stress cycle as n_1, n_2, $n_3 \cdots n_n$ respectively; Determine the alternating stress intensity $S_{tr}(1,2\cdots n)$ for each type of stress cycle; For each value $S_{tr}(1,2\cdots n)$, use the applicable design fatigue curves to determine the maximum number $N_{I(1,2\cdots n)}$ of cycle which would be allowable if this type of cycle were the only one acting. Calculate the usage factors from n_i/N_i; Calculate the cumulative usage factor from $U=\sum U_i$; Determine the component whether or not fatigue fails according to the Miner's linear cumulative usage criterion, $U=\sum U_i \leq 1.0$.

So far as the method is concerned, for the high stress case, D-β usage cure tends to be of linear relation. It is reasonable to use Miner's linear cumulative usage criterion. It tends towards conservative to consider the maximum amplitude of stress difference from the overall course of the operation condition and to take into account the mutual influence of the alternating stresses with different amplitude. It is affirmative to use $\Delta\sigma$-N curve that is superior to the σ-N curve and to take in to account the effect of elastic modulus and stress concentration. Meanwhile, there are two points worthy to be noticed. Firstly, the lifetime considered in the Code depends on the adopted value of the design fatigue cure test. If the final number of repetition N is taken as fatigue lifetime, N_1 is the number of repetition of micro-crack initiation, i.e. micro-crack initiation lifetime, $N_2=N_1+\Delta N_2$, is the macro-crack initiation lifetime of which ΔN_2 is the lifetime from micro-crack initiation to macro-crack initiation. ΔN_3 is the lifetime from macro-crack initiation to crack extension and till final failure. That is, $N= N_1+\Delta N_2+\Delta N_3$. The adopted value is directly related to the conservative margin. Secondly, because of the complex and diversity of the effect of environment and defects, it is understandable to adopt test data of small and slippery specimen in air with conservative process (20 times and doubled amplitude). But its conservatism shall be confirmed bye various test of effect of dimensions, environment and defects.

Simplified Fatigue Estimation

The all-around fatigue analysis is of too much work. In engineering practice, a simplified fatigue estimation method can be used to have approximate fatigue estimation for the key components. This method is described below. Perform exact finite element stress analyses for the RPV under the design transients of each condition. Select the extremum $S_{tresca\ max}$ using the extremum-selecting function of the program. The total stress of this kind of extremum includes peak stress. Select a typical condition according to the double factors, i.e. the maximum amplitude of stress variation and the maximum number of repetitions. Get the conservative boundary limit value through multiplying the usage factor at the extremum point of the representative condition by *m*—the major condition number. The sense consists in that, in the equation $U=\sum U_i$, $\sum U_i = \sum n_i/N_i$ is a number series, this series is not monotonous despite fluctuant. The first five terms of this series almost converged. Therefore, if let *m* be 6, the first six terms can cover all the series. While according to the analysis of the actual calculation, the adverse sign phenomenon of the couple of the stress variation amplitudes only exits in I_2 transient and Refueling transient of Level A condition and II-6 transient—Control Rod Drop transient of Level B condition. The cyclic types of larger amplitude and more repetition times are I_3 to I_6 transients and I_9 transient. After the above stress amplitudes pair, the amplitudes sharply decrease; the allowable number of repetitions logarithmically increases; n_3/N_3, n_4/N_4 tend to be less; the first 5 terms of the series nearly converged. Therefore, it is adequately conservative to let *m* be 6.

The basic idea of the fatigue estimation is as follows. Find the extrimum stress through filtering the result of the stress analysis under the design conditions. Cover all the locations of the RPV with several extremum points. Cover all the conditions with one or two representative conditions meeting the requirements of double factors. Obtain the estimated value U_s through multiplying the usage factor n_d/N_d at the extremum point of typical conditions by *m*. That is, $U_{s1} = m\ n_d/N_d$. Calculations and check demonstrate that the estimated value U_s is always greater than the analyzed value U.

The above mentioned method can be further simplified. As we know from the fatigue analysis of Vessel, the heatup and cooldown conditions make quite great contributions to the fatigue accumulative usage factor. These two conditions can be taken as typical condition and other kind of weighted factors can be used. If the total number of all Level A and Level B conditions is *M*, $U_{s2} = M\ n_{h\text{-}c}/N_{h\text{-}c}$.

The practical engineering calculations for Qinshan Phase I show, for bolts U=0.29, for other, 0.067; while U_{s1}=0.41, U_{s2}=0.43. It is sufficiently conservative.

BRIEF ANALYSIS OF OPERATION CONDITIONS

There are two key points in launching operation-feedback analysis. The first one is to ensure the structural integrity of the RPV under operation conditions. Lifetime management shall be carried out on material aging and components degradation for the RPV. There are four categories of factors that influence the structural integrity for the RPV during operation, i.e. radiation, fatigue, fracture and erosion. The second one is to check the prophase prediction. The operation loading spectra are obtained through monitoring and then the real conservative margin for design conditions is obtained. It is also to cumulate data for carrying out defect analysis for in-service inspection. The problem consists in that the monitoring system is whether or not capable to obtain the exact operation transients data. 1992 ASME Code XI IWB-3700 brings about that when an operating event causes an excursion outside the normal operating pressure and temperature limits defined in the plant technical specifications, an engineering evaluation shall be performed to determine the effects of the out-of-limit condition on the structural integrity of the reactor coolant system. Therefore, recording and detecting the abnormal operating pressure and temperature have been the requirements of the Code.

There have been five fuel cycles at Qinshan NPP Phase I up to now. As mentioned above, heatup and cooldown condition can be taken as typical conditions. Its typical figure and data are show in Fig.1 and Table 1.

The design limit values for the RPV are as follows: 150 heatup and cooldown circles respectively with the temperature up or down rate less or equal to 55℃/hour and the pressure up or down rate less or equal to 4.9MPa/hour. Table 1 shows that the actual temperature up or down rates are generally less than 60% of the limit value and the actual pressure up or down rates are generally less than 70% of the limit value. Although most cases are much lower and the stress amplitude decrease half, the allowable circles may increase 10 times, there are some cases that exceed the limit value in the early operation like T_{6+} and P_{6-}.

Table 1 the Data for the Five Fuel Cycles at Qinshan NPP Phase I

Circle Number		Temperature up or down rate (℃/h)		Pressure up or down rate (MPa/h)
Circle 1	T_{1-}	18.4	P_{1-}	1.6
	T_{1+}	13.5	P_{1+}	0.53
	T_{2-}	32.7	P_{2-}	3.5
	T_{2+}	17.5	P_{2+}	0.4
	T_{3-}	19.5	P_{3-}	2.17
	T_{3+}		P_{3+}	
	T_{4-}	14.7	P_{4-}	0.9
	T_{4+}	13.1	P_{4+}	1.04
	T_{5-}	28	P_{5-}	1.68
	T_{5+}	24.4	P_{5+}	0.59
	T_{6-}	26.1	P_{6-}	10.5
	T_{6+}	15(60)	P_{6+}	0.45
	T_{7-}	15.3	P_{7-}	1.4
	T_{7+}	12.9	P_{7+}	1.68
	T_{8-}	15.5	P_{8-}	0.82
	T_{8+}	8.5	P_{8+}	0.92
	T_{9-}	31	P_{9-}	2.4
	T_{9+}	13.8	P_{9+}	1.12
	T_{10-}	17.3	P_{10-}	2.15
	T_{10+}		P_{10+}	
Circle 2	T_{1-}	23.2	P_{1-}	1.02
	T_{1+}	7.95	P_{1+}	0.65
	T_{2-}	22	P_{2-}	1.22
	T_{2+}		P_{2+}	
Circle 3	T_{1-}	12.5	P_{1-}	1.22
	T_{1+}	22.2	P_{1+}	2.71
Circle 4	T_{1-}	16.5	P_{1-}	0.87
	T_{1+}	25	P_{1+}	1.83
	T_{2-}	17	P_{2-}	1.22
	T_{2+}	32.8	P_{2+}	1.56
	T_{3-}	15	P_{3-}	0.87
	T_{3+}	33	P_{3+}	2
Circle 5	T_{1-}		P_{1-}	1.93
	T_{1+}	25	P_{1+}	1.19
	T_{2-}	16	P_{2-}	2.22

FEEDBACK OF RADIATION MONITORING

Fig.2 and Fig.3 show the neutron fluence and P−T limit curves under design and operation conditions for Qinshan NPP Phase I. The neutron fluence is calculated according to one-dimensional calculation of ANISN and is rectified by two-dimensional calculation. The selection of margin is discussed according to the comparison between NRC RG 1.99 Rev.1 (1997) and NRC RG 1.99 Rev.2 (1988). Compared with the 16EFPY and 32EFPY P−T limit curves of B/B (Braidwood) reactor, the selected margin is appropriate and adequately conservative. The radiation monitoring data of 3EFPY and 5.4EFPY are 64°C and 72°C respectively, compared with in-service hydrostatic test temperature. The 24EFPY data is predicted as 128°C including the 25°C margin of material and instruments.

Because of the experience got from the Qinshan NPP Phase I, calculated according to NRC RG1.99 Rev.2 (1988) for the PC reactor, which is similar to Qinshan NPP Phase I, the selected margin has a quite large reduction in comparison with the prototype reactor. Its P−T limit curves are shown in Fig.4 and Fig.5. 32EFPY in-service hydrostatic test temperature is 105°C.

CONCLUSION

As far as the above mentioned goes, there is few excursion outside the normal operating pressure and temperature limits defined in the plant Technical Specifications during operation because the sufficient margin has been considered in the design of the RPV. But the integrated and archived transient records not only provide the basis for component analysis but also reflect the level of operation and management. What is more, they create conditions for life-prolonging.

REFERENCES

[1] J.D. QU, Y.K. DOU and Y.B. HE, Mechanical Analysis of Structural Integrity and Research on Site Measurement for RPV of Qinshan NPP, China Nuclear S & T Report, CNIC-01081 SNERDI-0030, Atomic Energy Press, 1996. 4, SMiRT-14, FW/9

[2] J.D. QU, The Stress Analysis Systems for the Nuclear Vessel, Nuclear Power Engineering, 1983, 5 (4), 72-82

[3] K. Shibata, D. Kato and Y.S. Li, Development of PFM Code for Evaluating Reliability of Pressure Components Subjected to Transient Loading, in SMiRT-15, Seoul, Korea, 1999.8. M 01/2

[4] S.G. Jung, H.S. Kim, T.E. Jin etc., The Estimation of Critical RTNDT and Probability of Failure for PWR vessels, in SMiRT-15, Seoul, Korea, 1999.8. D 01/7

[5] J.D. QU, P.Z. WANG and S.Q. XIE, Strain Measurement and Analysis for the RPV of Qinshan NPP(unit 1) at Primary System Hydrostatic Test, Chinese Journal of Nuclear Science & Engineering, 1 (14), 1994, 1-10

[6] J.D. QU and Y.K. DOU, SMEC :A Transient Sealing Analysis Program System for Nuclear Vessel, Nuclear Power Engineering, 4(8) 1987, 52-57

[7] J.D. QU, Comprehensive Solving of Axisymmetric Coupled Thermoelastic Contact Problem under Covariant Loading, Mechanics 2000 ,Weather Press , 2000, 629

[8] J.D. QU, P.Z. WANG, Y.K. DOU et al ,Tests and Analysis of Sealing Characteristics under Thermal Transient on a Nuclear PV Model, in Proceedings of the 6-th ICPVT, Beijing, 1988, Vol.1, 239-248

[9] J.D. QU, Y.K. DOU, Sealing Analysis for Nuclear Vessels of PWR, in Transactions of the 9-th IC on SMiRT, Lausanne, Switzerland, 1987, G8/7

[10] J.D. QU, Y.K. DOU and S.M. Zhu, Site Ultrasonic Measurement on RPV Stud-bolt Loading under Hot Transient of Qinshan NPP, in ICPVT-8, Montreal, Canada, 1996, Vol.1, 333-336

[11] J.D. QU, Y.K. DOU and P.Z. WANG, Thermal Analysis for the Sealing Test on a RPV Model, in SMiRT-10, Anaheim USA, 1989, F8/2

[12] J.D. QU, Y.B. HE, Y.G. WANG et al, Research on Ultrasonic Measurement for the Welding Residual Stress in the Girth Welds for a RPV, in SMiRT-14,Lyon,France, 1997, BCDW/18

[13] Chinese Nuclear Standard EJ/T 1033-1996 , Assessment Criteria for Preventing fast Rupture of RPV of PWR NPP

[14] J.D. QU, Summarization of Fatigue Analysis and Simplified Fatigue Estimation on the RPV, 8th National Conference on SMiRT, Chengdu, 1994, 154-159

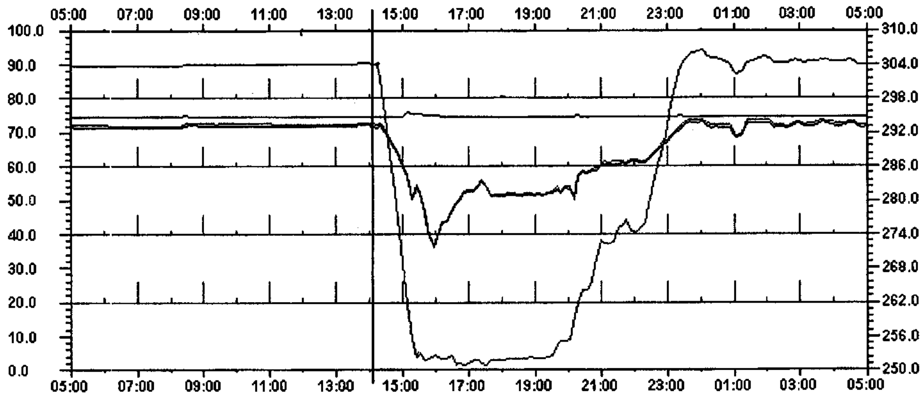

Fig.1 A Typical Figure of the Plant Cooldown and heatup Transient Curves

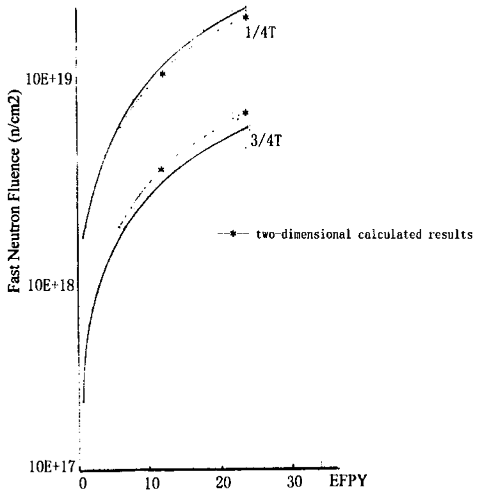

Fig.2 The relation between Fast Neutron Fluence and EFPY For Qinshan NPP

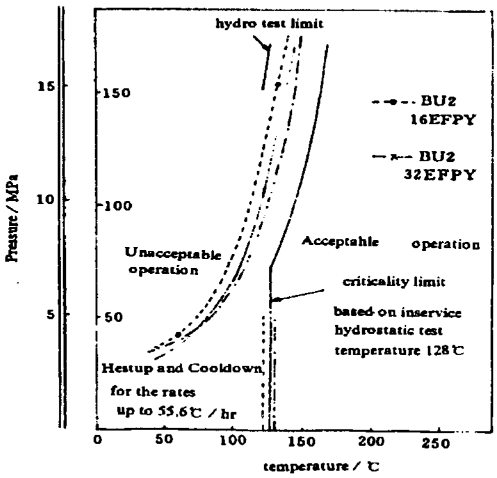

Fig.3 The P-T limit curves for Qinshan NPP

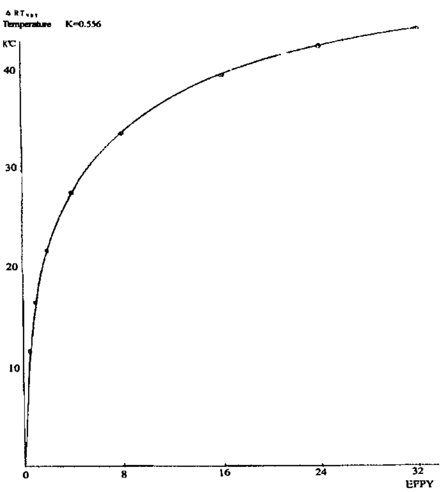

Fig.4 The Relation between Fast Neutron Fluence and EFPY For PC NPP

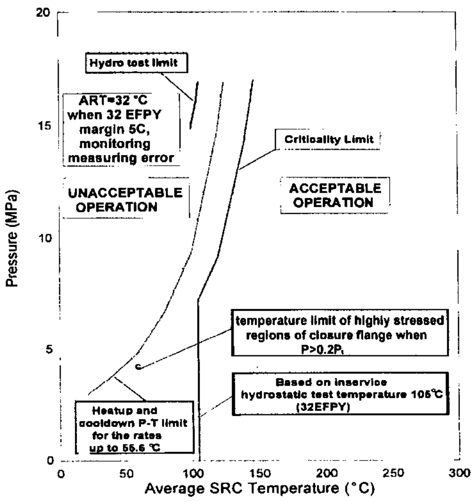

Fig.5 The P-T limit curves for PC NPP