MATERIAL AND FABRICATION OF THE HTTR REACTOR PRESSURE VESSEL

XA9846689

Y. TACHIBANA, K. KUNITOMI, S. SHIOZAWA
Japan Atomic Energy Research Institute,
Oarai-machi, Ibaraki-ken

T. ASAMI, S. YAMAGUCHI
Babcock-Hitachi K.K.,
Hiroshima

Japan

Abstract

The High Temperature Engineering Test Reactor (HTTR) is under construction at Oarai Research Establishment, Japan Atomic Energy Research Institute (JAERI) and planned to be critical in October 1997. Fabrication of the HTTR reactor pressure vessel (RPV) at Kure Works, Babcock-Hitachi K. K. took about two years, and the RPV was transported to the Oarai site in August 1994. Pressure test of the primary and secondary cooling system including the RPV was performed successfully in March 1996 [1].

Because temperature of the HTTR RPV becomes about 400 °C at normal operation, 2 1/4 Cr-1 Mo steel is chosen for it. Fluence of the RPV is calculated to be less than 1×10^{17} n/cm^2 (E>1 MeV), and so irradiation embrittlement is presumed to be negligible, but temper embrittlement is not. For the purpose of reducing embrittlement, content of some elements is limited on 2 1/4 Cr-1 Mo steel for the HTTR RPV using embrittlement parameters: J-factor and $\overline{X}$.

In this paper design and structure of the HTTR RPV is briefly reviewed first. Fabrication procedure of the RPV and its special feature is shown. Material data on 2 1/4 Cr-1 Mo steel manufactured for the RPV, especially the embrittlement parameters J-factor and $\overline{X}$, and nil-ductility transition temperatures T_{NDT} by drop weight tests, are shown, and increase in the transition temperature is estimated based on data available in literature. Technology of the HTTR RPV is applicable to RPVs of future commercial High Temperature Gas-cooled Reactors (HTGRs).

1. Design and structure

Table 1 and Fig. 1 show specifications and schematic diagram of the HTTR RPV respectively. The RPV consists of a RPV top head, which includes thirty-one stand-pipes, a top head dome, a top head flange, thermal shields, etc., and a RPV body containing a shell flange, a shell, three stand-pipes, a bottom head petal, a skirt, a bottom head dome, a support ring, radial keys, etc. The RPV top head is bolted to the RPV body by 72 stud bolts. The thirty-one stand-pipes, which include sixteen for control rods, five for irradiation test, three for surveillance test, three for neutron detection, two for in-service inspection of reactor internals, and two for measurement of temperatures and core differential pressure are welded to nozzles on the top head dome. Figure 2 shows arrangement of stand-pipes on the top head dome. The largest seven stand-pipes, N1 to N7, are also used for refueling. Three other stand-pipes for hot plenum temperature measurement and fuel failure detection are welded to nozzles on the shell. Figure 1 shows one of the three stand-pipes. The skirt supports weight

Table 1. Major specification of the HTTR reactor pressure vessel

Design pressure	4.7 MPa [gauge]
Design Temperature	440 °C
Normal operating pressure	3.9 MPa [gauge]
Inlet coolant temperature	395 °C
Inside diameter	5.5 m
Height	13.2 m
Thickness of cylindrical shell and bottom head dome	122 mm [minimum]
Thickness of top head dome	160 mm [minimum]
Number of stand-pipes	34
Material	2 1/4 Cr-1 Mo steel (Normalized and tempered)

and seismic load of the reactor. Horizontal seismic load is sustained by six stabilizers and a stand-pipe support beam as well as the skirt. The support ring support vertical load of the core, and the radial keys hold horizontal movement of the core through core restraint mechanism. The thermal shields are made up of layers of metallic plates, which protect the RPV top head from overheating, especially in loss of forced coolant circulation accidents.

Because temperature of the HTTR RPV becomes about 400 °C at normal operation, 2 1/4 Cr-1 Mo steel, normalized and tempered, which has higher creep rupture strength than Mn-Mo steel for RPVs of Light Water Reactors, is chosen for it. Three kinds of 2 1/4 Cr-1 Mo steel: forgings of Japan Industrial Standard (JIS) specification SFVAF22B, equivalent to ASTM A-336 Gr. F22, Cl. 3, plates of JIS SCMV4-2, equivalent to ASTM A-387 Gr. 22, Cl. 2, and seamless pipes of JIS STPA24, equivalent to ASTM A-335 Gr. P22 are used for components as shown in Fig. 3, which also shows weld lines.

The safety evaluation criteria for temperatures of the HTTR RPV are as follows: maximum temperature shall not exceed 500 °C in anticipated operational occurrences and 550 °C in accidents. The maximum temperature of the RPV in the depressurization accident is calculated to be about 530 °C [2].

2. Fabrication

Figure 4 shows fabrication procedure of the HTTR RPV. As shown in Figs. 3 and 4, two types of stand-pipes exist, designated "Stand-pipe a" and "Stand-pipe b" in Fig. 4: a forging, and a forging and a pipe welded together respectively. The inner nineteen stand-pipes for control rods and irradiation tests, which require dimensional accuracy in manufacturing, are forgings. Heads of the outer twelve stand-pipes on the top head dome and three stand-pipes on the shell are forgings, which are welded to seamless pipes, making up the "Stand-pipe b."

The top head dome is a very large forging, and nineteen nozzles for the inner nineteen stand-pipes above are integrated with itself, that is there are no weld lines between the dome and the nozzles. Since gaps among the nineteen nozzles are so narrow, it is impossible to perform in-service inspection: ultrasonic testing, of the weld lines when they exist. Ultrasonic testing of the weld lines between the stand-pipes and the nozzles is possible utilizing special equipment for it. The other thirteen nozzles including a manhole nozzle, are welded to the top head dome. Regarding these weld lines, it is possible to conduct ultrasonic testing, because there is enough distance between the nozzles, and the weld lines are accessible from

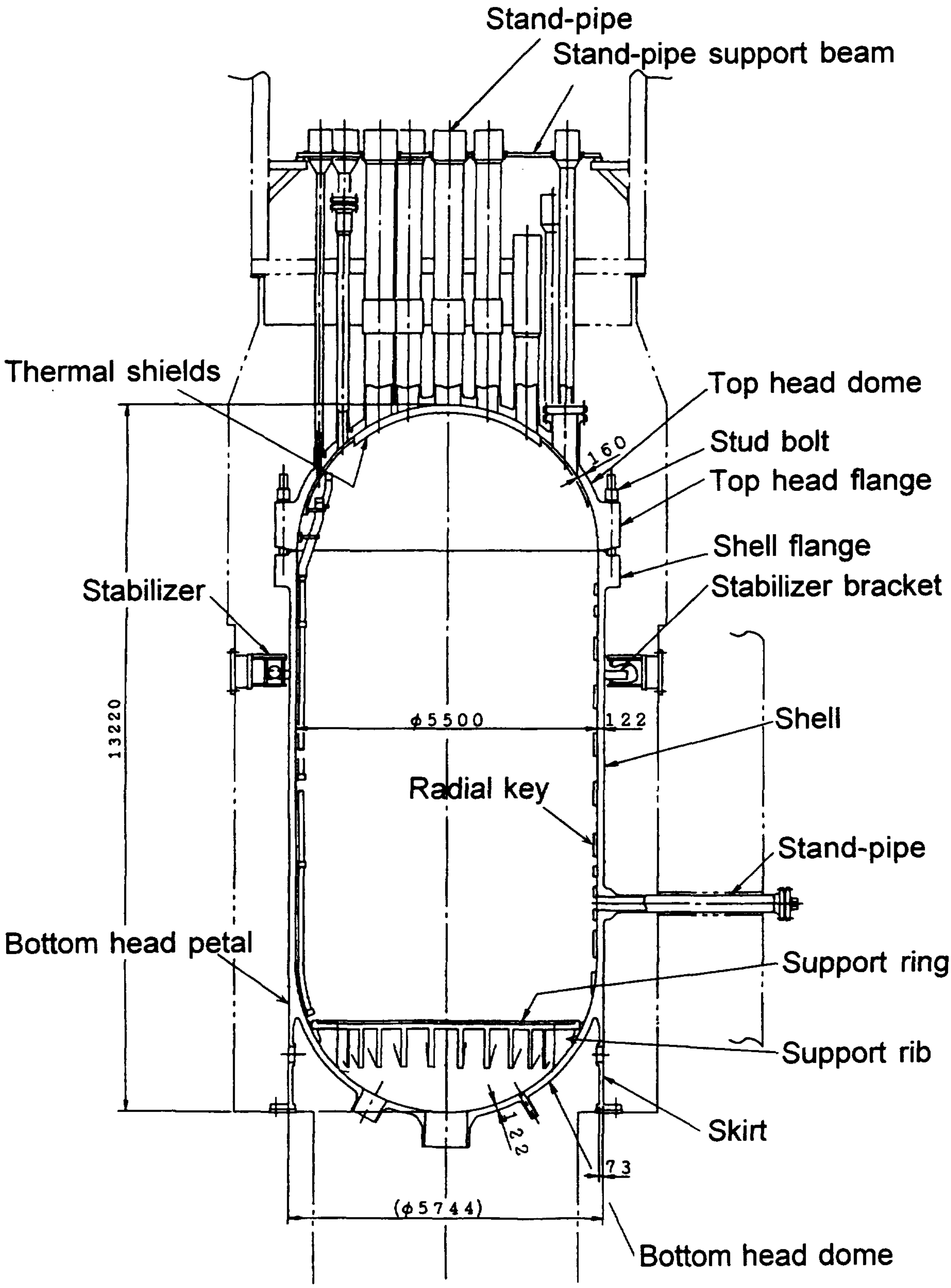

Fig. 1 Schematic diagram of the HTTR RPV

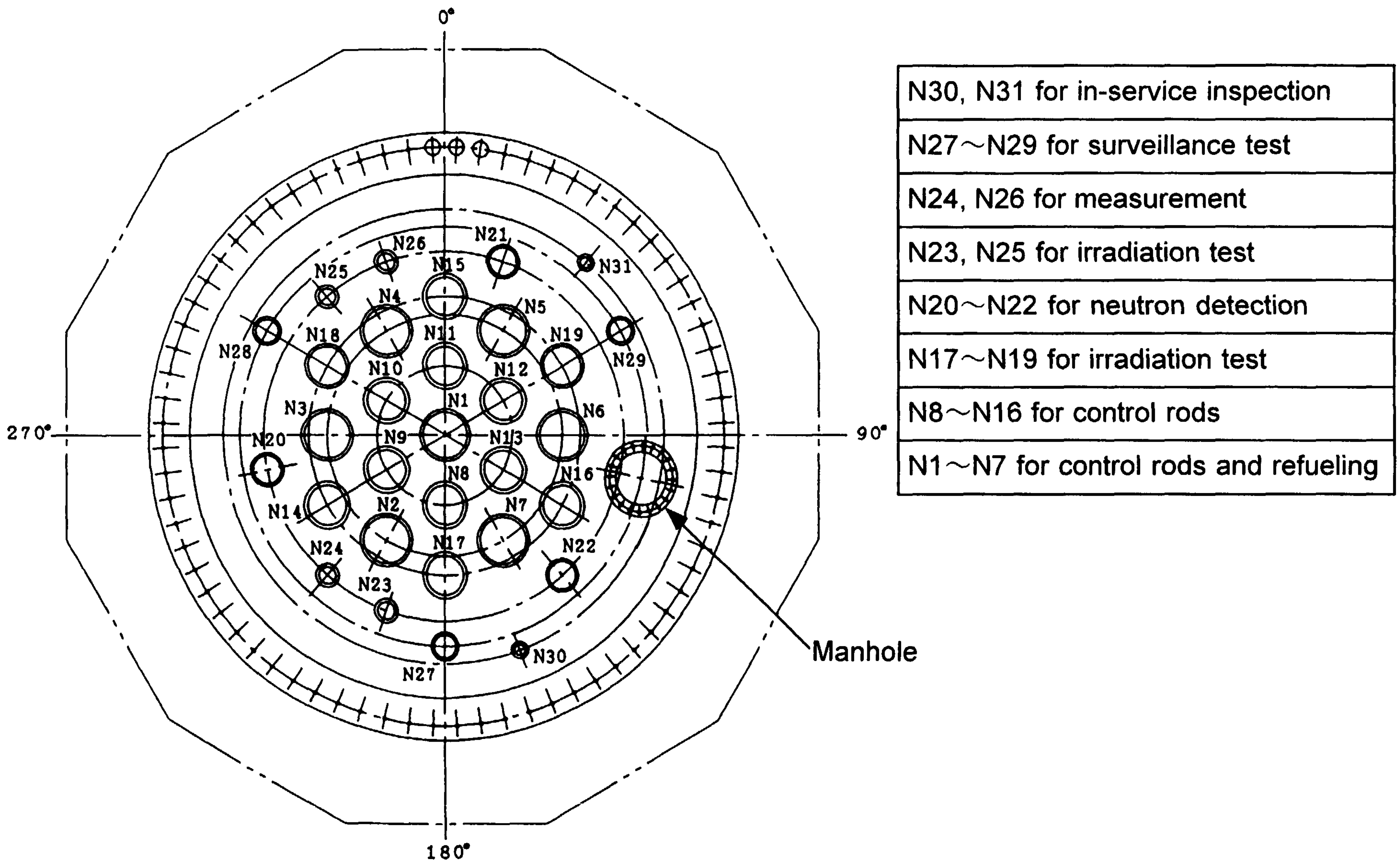

Fig. 2 Arrangement of stand-pipes of the HTTR RPV

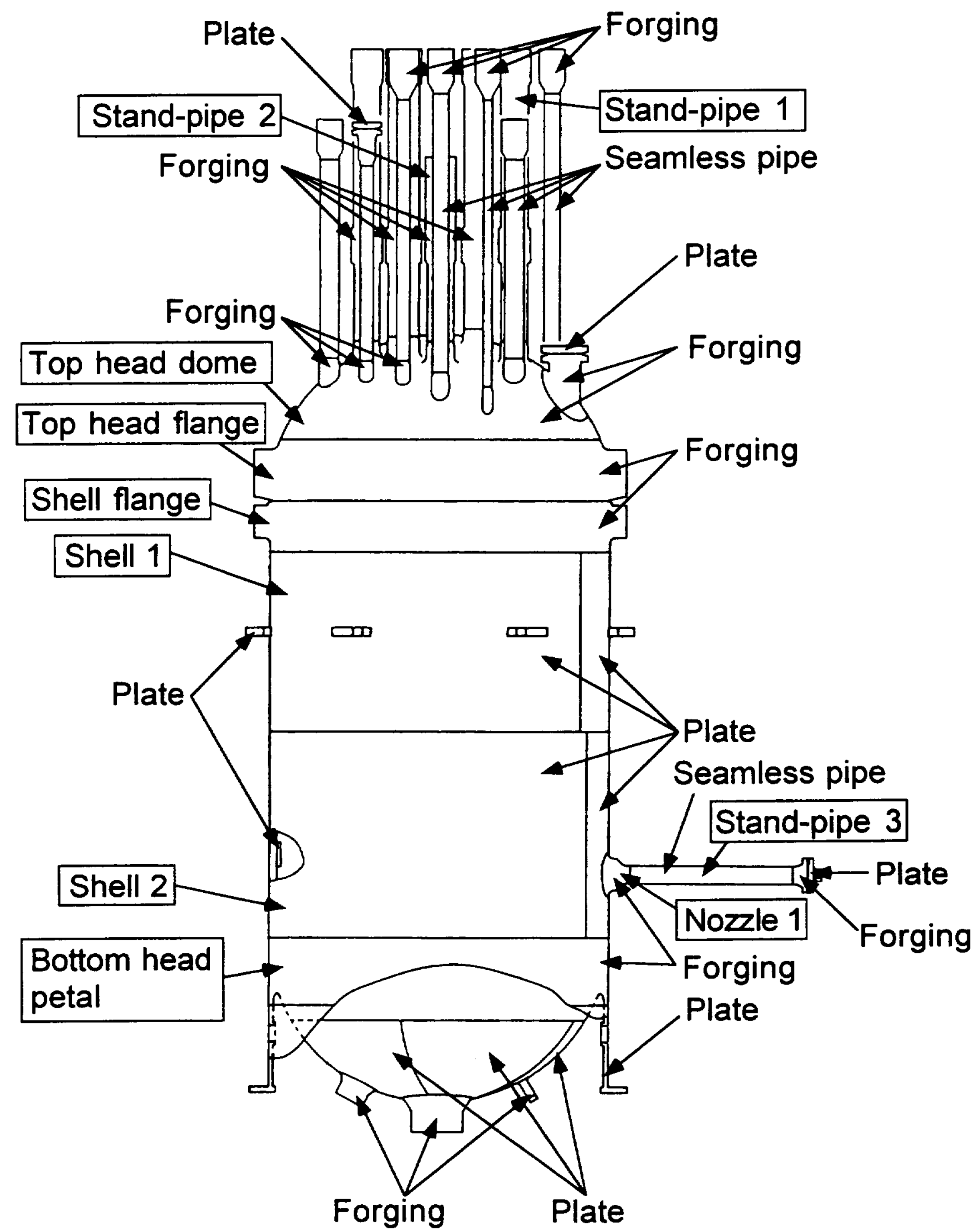

Plate : JIS SCMV4-2, Forging : JIS SFVAF22B,
Seamless Pipe : JIS STPA24

Fig. 3 Material and weld lines of the HTTR RPV

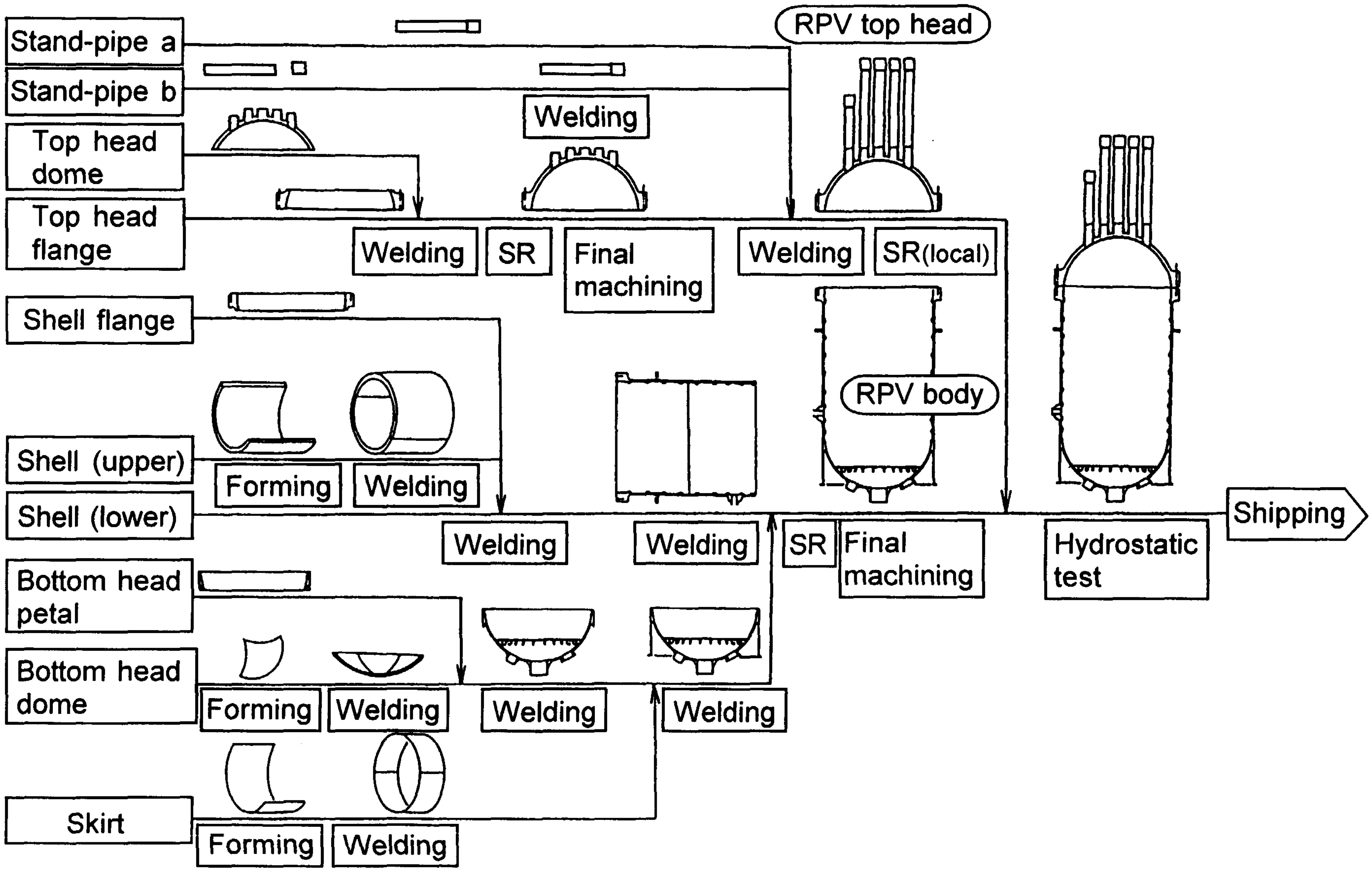

Fig. 4 Fabrication procedure of the HTTR RPV

outside. After welding the top head dome to the upper flange, a large forging, stress relieving (SR) and final machining was performed. Then stand-pipes were welded to the top head dome, followed by local stress relieving as shown in Fig. 4.

Cylindrical shell of the HTTR RPV is made up of four plates formed and welded together as shown in Figs. 3 and 4. The shell was welded to the shell flange, a large forging. The bottom head petal, a large forging, was welded to the bottom head dome, which consists of formed four plates, and the skirt. These were then welded together, building up the RPV body, and stress relieving and final machining was conducted.

For the welding of the large components, automatic narrow-gap (groove) MIG welding, developed by Babcock-Hitachi, K. K. and schematically shown in Fig. 5, was mainly utilized. The narrow-gap MIG welding is superior to ordinary submerged arc welding (SAW) in the following points:

(i) higher ductility of weld and narrower heat-affected zone is attained because of smaller heat input,

(ii) smaller number of path reduces probabilistic occurrence of weld defect,

(iii) smaller amount of welding consumables is needed by adopting square groove.

Hydrostatic test of the RPV at the fabricator was performed before shipping. The RPV was transported to Oarai Research Establishment, JAERI in August 1994. After the installation of the RPV body into the containment vessel, reactor internals started to be installed, which was followed by closing of the RPV top head in October 1995. After that stand-pipe closures with control rods, surveillance holders, etc. were fixed. Pressure test of the primary and secondary cooling system including the RPV was performed successfully in March 1996.

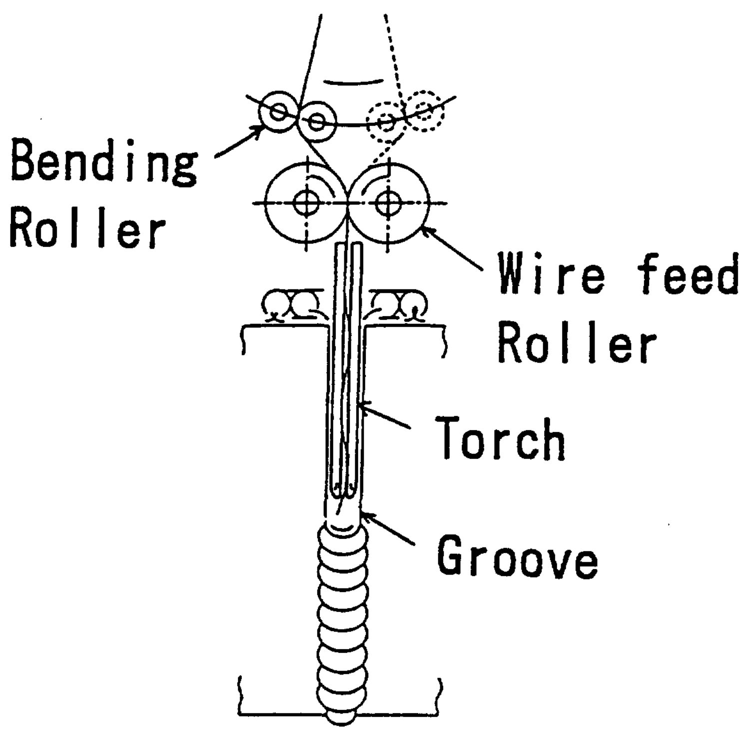

Fig. 5 Mechanism of automatic narrow-gap MIG welding

3. Material

Because fluence of the RPV is calculated to be less than 1×10^{17} n/cm^2 (E>1 MeV), neutron irradiation embrittlement is presumed to be negligible. However, the integrity of the RPV can be impaired due to temper embrittlement at 400 °C. For the purpose of reducing embrittlement, content of some elements is limited on 2 1/4 Cr-1 Mo steel for the HTTR RPV using embrittlement parameters:

$$\text{J-factor} = (\text{Si+Mn})(\text{P+Sn}) \times 10^4 \leq 100 \quad (\text{Si, Mn, P, Sn : wt\%}) \tag{1}$$

$$\overline{\text{X}} = (10\text{P+5Sb+4Sn+As})/100 \leq 10 \quad (\text{P, Sb, Sn, As : ppm}) \tag{2}$$

which is called HTGR specification and applied to both base metal and weld metal. J-factor is a commonly used parameter proposed by Watanabe et al. [3]. This factor implies that the impurities Si (silicon) and Mn (manganese) alone in the absence of P (phosphorus) and Sn (tin) cannot cause any embrittlement. Similarly in the absence of Si and Mn, P and Sn, do not cause any embrittlement. It is indicated by Viswanathan and Jaffee [4] that the former coincide with their study but the latter does not, that is Si and/or Mn do not cause temper embrittlement in the absence of the impurity elements P and Sn, however, the combination (P+Sn) is capable of causing significant embrittlement in the absence of Mn and Si contrary to the predictions of the J-factor. Thus it is necessary to employ the other parameter $\overline{\text{X}}$.

Base metal

Figure 6 shows J-factor and $\overline{\text{X}}$ of nineteen heats of manufactured 2 1/4 Cr-1 Mo steels for the HTTR RPV. J-factor and $\overline{\text{X}}$ ranges from 25 to 55 and from 4.1 to 8.3 respectively, which satisfies the HTGR specification. Regarding the plates and four large forgings, the top head dome, top head flange, shell flange, and bottom head petal, which consist main part of the RPV, J-factor and $\overline{\text{X}}$ are less than 38 and 5.1 respectively. For these nineteen heats of 2 1/4 Cr-1 Mo steel, J-factor and $\overline{\text{X}}$ exhibit almost linear relation. Chemical composition and the embrittlement factors, J-factor and $\overline{\text{X}}$, of ten components of the RPV are shown in Table 2, see also Fig. 3 pointing the components with names in boxes.

Figure 7 shows one example of correlation between J-factor and increase in 50 percent ductile-to-brittle fracture appearance transition temperatures (ΔFATT) from the paper by Viswanathan and Jaffee [4]. According to the figure, which arranges long term (20,000 to 60,000 hr) isothermal embrittlement studies in the range 343 °C to 510 °C on numerous heats of commercial, heavy section 2 1/4 Cr-1 Mo steels in a variety of product forms, the ΔFATT becomes less than 10 °C when J-factor is less than 50. Most components of the HTTR RPV fulfill this condition except some medium and small forgings whose values exceed it a little.

Figure 8 shows distribution of nil-ductility transition temperature, T_{NDT}, correlated to J-factor. The figure contains 68 results (some of which overlap each other) of drop weight tests on the components made from the nineteen heats of steels. It should be noted that for all the components reference temperatures, RT_{NDT}, became equal to the nil-ductility transition temperatures, T_{NDT}. The T_{NDT} or RT_{NDT} lies in the range -80 °C to -30 °C, satisfying another HTGR specification that RT_{NDT} should be less than -20 °C. Because T_{NDT} depends on manufacturing process, the results scatter for components of the same heat. Although J-factor is usually related to increase in ductile-to-brittle transition temperatures, it seems to have weak correlation with T_{NDT}.

Table 2. Chemical composition and reference temperature (RT_{NDT}) on some components of HTTR reactor pressure vessel

(wt%)

Forging (ladle analysis)	C	Si	Mn	P	S	Cr	Mo	Cu	Ni	V	Co	Al	Sn	As	Sb	$\overline{X}$ (ppm)	J (wt%)	RT_{NDT} (°C)
JIS spec. (SFVAF 22B)	≤0.15	≤0.50	0.30~ 0.60	≤0.030	≤0.030	2.00~ 2.50	0.90~ 1.10											
HTGR spec.																≤10	≤100	≤-20
Top head dome	0.14	0.07	0.55	0.003	0.001	2.29	1.06	0.04	0.08	0.005	0.008	<0.005	0.003	0.003	0.0009	5.0	37.2	-50
Top head flange	0.14	0.04	0.54	0.003	0.001	2.29	1.05	0.04	0.09	0.005	0.009	<0.005	<0.003	0.004	0.0010	5.1	34.8	-65
Shell flange	0.14	0.03	0.54	0.003	0.003	2.29	1.00	0.03	0.10	0.005	0.008	<0.005	<0.003	<0.003	0.0010	5.0	34.2	-55
Bottom head petal	0.15	0.05	0.55	0.003	0.001	2.30	1.05	0.03	0.04	0.005	0.007	<0.005	<0.003	0.003	0.0011	5.0	36.0	-35
Nozzle 1	0.13	0.07	0.46	0.006	0.002	2.44	1.05	0.02	0.04	0.006	0.007	0.003	0.003	0.002	0.0006	7.7	47.7	-40
Stand-pipe 1	0.12	0.10	0.45	0.005	0.003	2.32	1.03	0.03	0.04	0.006	0.006	0.003	0.003	0.002	0.0007	6.8	44.0	-60
Stand-pipe 2	0.14	0.10	0.46	0.006	0.004	2.37	1.05	0.03	0.06	0.007	0.007	0.003	0.003	0.003	0.0008	7.9	50.4	-65
Plate (ladle analysis)	C	Si	Mn	P	S	Cr	Mo	Cu	Ni	V	Co	Al	Sn	As	Sb	$\overline{X}$ (ppm)	J (wt%)	RT_{NDT} (°C)
JIS spec. (SCMV4-2)	≤0.17	≤0.50	0.30~ 0.60	≤0.030	≤0.030	2.00~ 2.50	0.90~ 1.10											
HTGR spec.																≤10	≤100	≤-20
Shell 1	0.15	0.10	0.55	0.003	0.001	2.45	1.06	0.01	0.15	0.010	0.006	0.019	0.001	0.002	<0.001	4.1	26.0	-55
Shell 2	0.14	0.10	0.57	0.004	0.001	2.43	1.05	0.01	0.17	0.010	0.006	0.011	0.001	0.002	<0.001	5.1	33.5	-55
Seamless pipe (ladle analysis)	C	Si	Mn	P	S	Cr	Mo	Cu	Ni	V	Co	Al	Sn	As	Sb	$\overline{X}$ (ppm)	J (wt%)	RT_{NDT} (°C)
JIS spec. (STPA24)	≤0.15	≤0.50	0.30~ 0.60	≤0.030	≤0.030	1.92~ 2.60	0.87~ 1.13											
HTGR spec.																≤10	≤100	≤-20
Stand-pipe 3	0.11	0.02	0.48	0.005	0.002	2.35	0.99	0.02	0.05	0.010	0.004	0.002	0.002	0.002	0.001	6.5	35.0	-30

Note: RT_{NDT} (reference temperature) was equal to T_{NDT} (nil-ductility transition temperature) regarding all the components above.

Weld	C	Si	Mn	P	S	Cr	Mo	Cu	Ni	V	Co	Al	Sn	As	Sb	$\overline{X}$ (ppm)	J (wt%)	RT_{NDT} (°C)
JIS spec. of wire (YG2CM-A)	≤0.15	0.20~ 0.90	0.40~ 1.40	≤0.025	≤0.025	2.10~ 2.70	0.90~ 1.20	≤0.40										
HTGR spec.																≤10	≤100	≤-20
Wire	0.12	0.38	0.86	0.007	0.007	2.33	1.12	0.01			0.002							
Weld metal	0.12	0.22	0.63	0.005	0.006	2.25	1.05	0.03	0.02	0.003	0.003	0.004	0.002	0.002	0.001	6.0	60.0	-35

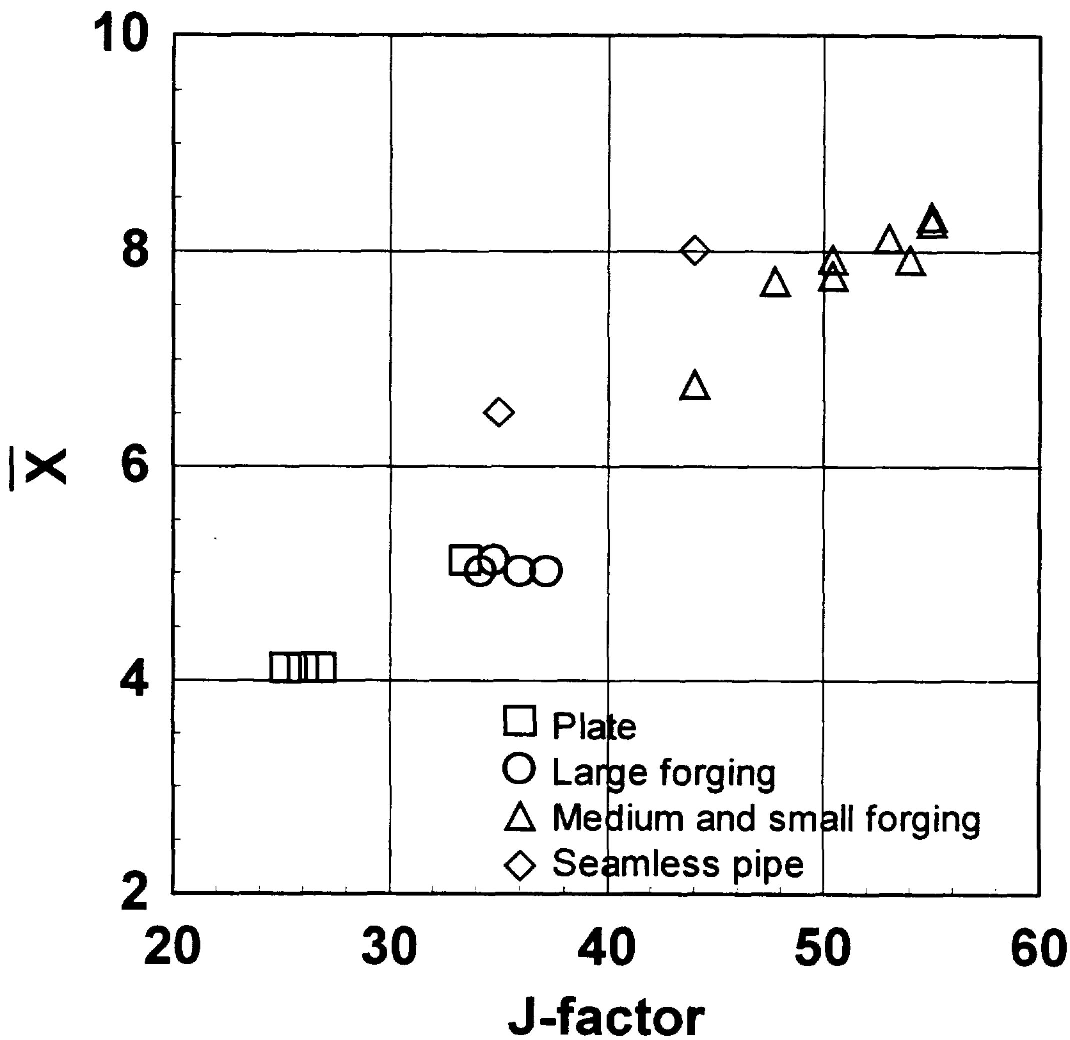

Fig. 6 Distribution of $\overline{X}$ and J-factor on 2 1/4 Cr -1 Mo steel for the HTTR RPV

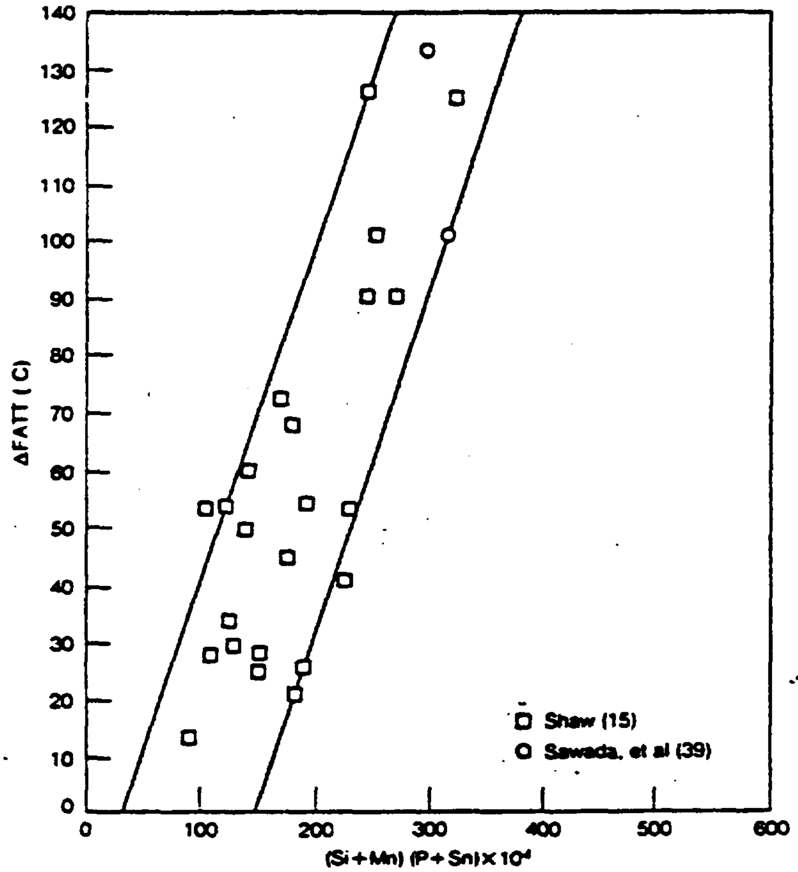

Fig. 7 Correlation between J-factor and ΔFATT by Viswanathan and Jaffee [3]

Weld metal

The embrittlement parameters, J-factor and $\overline{X}$, derived by check analysis of weld metal of the HTTR RPV ranged from 60 to 84 and 6.0 to 9.0 respectively, which satisfies the HTGR specification. The values of J-factor of weld metal are larger than those of base metal, because content of silicon (Si) and manganese (Mn) of the weld metal is higher than that of the base metal, as shown in Table 2. Applying the J-factor to Fig. 7, maximum embrittlement potential (ΔFATT) of the weld metal is estimated to be roughly 30 °C. The ΔFATT at 400 °C, which is temperature of the HTTR RPV at normal operation, is predicted to be lower than the estimated value, because Fig. 7 includes data at as high as 510 °C.

Thus it is concluded that increase in reference temperatures RT_{NDT} on the HTTR RPV due to irradiation and temper embrittlement is presumed to be small for both the base and weld metal.

Fracture toughness requirements

For the purpose of preventing brittle fracture, Japanese regulation on fracture toughness requirements on RPVs for Light Water Reactors, which is based on ASME Code Section III and Nuclear Regulation Commission 10CFR Ch. 1 Part 50 Appendix G, is applied to the HTTR RPV. For example, the temperature of the closure flange regions that are highly stressed by the bolt preload must exceed the reference temperature of the material in those regions by at least 67 °C (120 °F) for normal operation, when pressure exceeds 20 percent of the preservice system hydrostatic test pressure. Because reference temperature of the weld

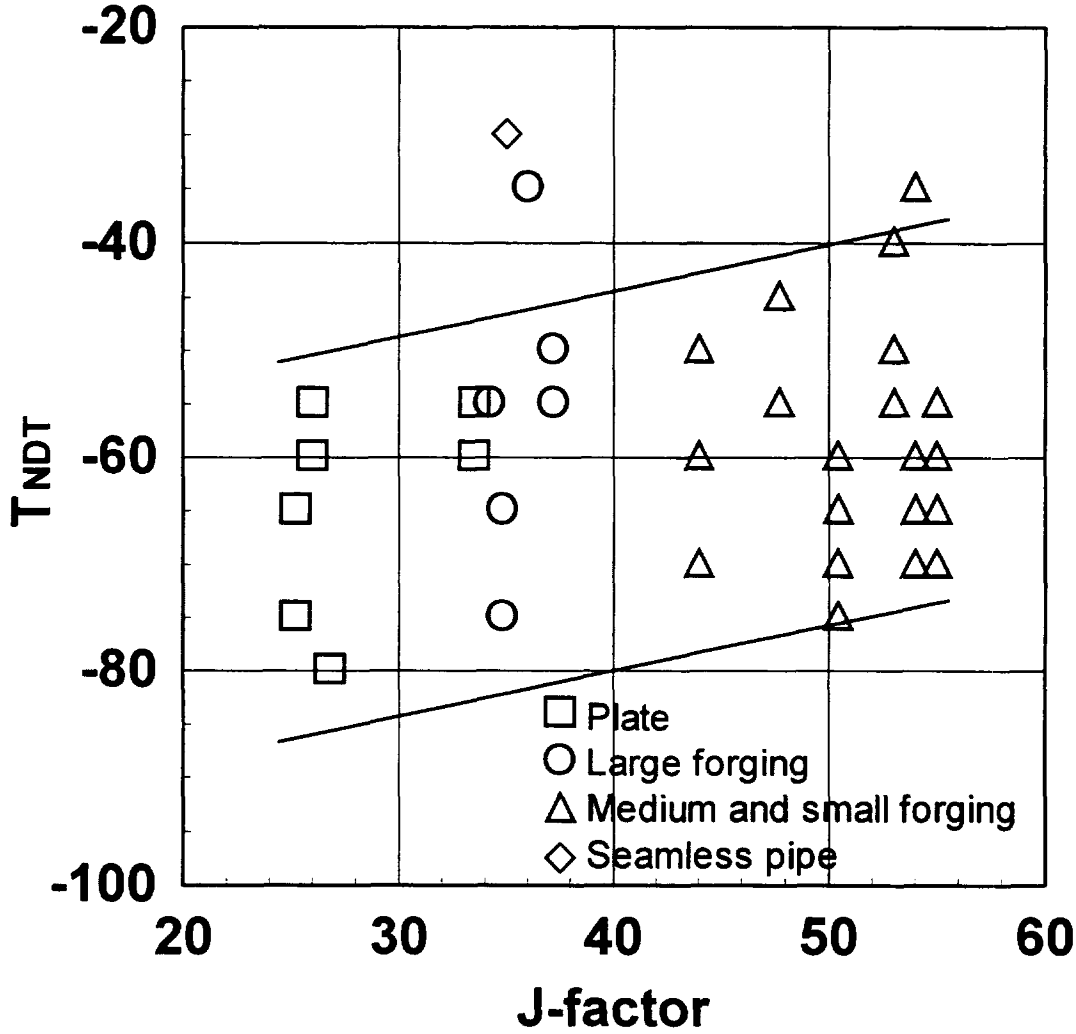

Fig. 8 Relation between T_{NDT} and J-factor on 2 1/4Cr-1Mo steel for the HTTR RPV

metal is -35 °C as shown in Table. 2, temperatures of the top head and shell flange of the HTTR RPV must exceed 52 °C:

-35 + 67 + 20 (predicted increase in reference temperature) =52 (°C)

at normal operation including start-up of the reactor.

Though primary coolant of the HTTR can be preheated by three primary gas circulators before start-up of the reactor, temperature of the primary helium coolant with small heat capacity decreases rapidly when secondary (water) cooling system start operating. Thus special start-up procedure has to be taken for the HTTR, which is still being considered.

Surveillance test

Surveillance tests on materials of the HTTR RPV will be performed in order to examine transition of mechanical properties of the materials due to irradiation and temper embrittlement. In addition to the mandatory tensile test and Charpy impact test, fracture toughness test for determination of J_{IC}, and test based on Magnetic Interrogation Method [5] for assessment of material deterioration and remaining life of the RPV. Surveillance test items are shown in Table. 2.

Surveillance test specimens are stored in 12 holders, which are installed close to inner surface of cylindrical shell of the RPV. During the operation of the HTTR for 20 years, the specimen holders are taken out four times: three holders at a time. The post-irradiation tests are planned to be performed at JMTR hot laboratory, JAERI. Temperature and dose of the specimens are measured by temperature monitors and dosimeters stored in the holder respectively.

4. Conclusion

Fabrication, examination and testing of the HTTR RPV completed successfully in March 1996. By limiting content of elements on 2 1/4 Cr-1 Mo steel, especially impurities of Si, P, Sb, and Sn, temper embrittlement as well as irradiation embrittlement of the RPV is presumed to be small.

Table 3. Surveillance test items of the HTTR reactor pressure vessel

	Plate			Forging
	(base metal,	H. A. Z.,	weld metal)	(base metal)
Tensile test	O	O	O	O
Charpy impact test	O	O	O	O
Fracture toughness test	O	O	O	O
Magnetic Interrogation Method [5]	O	O	O	-

References

[1] S. Terado, Y. Tachibana, K. Kunitomi, and Y. Fukaya, "Design and Fabrication of HTTR Reactor Pressure Vessel," Report of the Japan Atomic Energy Research Institute, JAERI-Tech 96-034, 1996. (in Japanese)

[2] S. Saito, et al., "Design of High Temperature Engineering Test Reactor (HTTR)," Report of the Japan Atomic Energy Research Institute, JAERI 1332, 1994.

[3] J. Watanabe, et al., "Temper Embrittlement of 2 1/4 Cr-1 Mo Pressure Vessel Steel," Presented at ASME 29th Petroleum Mech. Eng. Conf., Dallas, Sept. 15-18, 1974.

[4] R. Viswanathan and R. I. Jaffee, "2 1/4 Cr-1 Mo Steels for Coal Conversion Pressure Vessels," Journal of Engineering Materials and Technology, Vol. 104, pp. 220-226, 1982.

[5] K. Ara, N. Nakajima, N. Ebine, K. Sakasai, "Magnetic Interrogation Method for Nondestructive Measurement of Radiation Hardening of Nuclear Reactor Pressure Vessels," Proc. of 8th Int. Conference on Pressure Vessel Technology, Canada, pp.183-189, 1996.