

**NUCLEAR ENGINEERING**

**MASSACHUSETTS INSTITUTE  
OF TECHNOLOGY**

**Investigations  
of  
ORNL Pressurized Thermal Shock Experiments  
by  
Dong W. Jerng and Robert G. Carter  
Report No. MITNE-300  
March 30, 1992**



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## **Foreword**

This report is prepared under the contract (Contract No. : Pending ) between Yankee Atomic Electric Company and Massachusetts Institute of Technology.

Principal investigator: Neil. E. Todreas, Professor  
Nuclear Engineering Dept., M.I.T  
Research assistant: Dong W. Jerng, Postdoctoral Associate  
Nuclear Engineering Dept. M.I.T.  
Project Monitor : Robert G. Carter, Senior Engineer  
Yankee Atomic Electric Company

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## **1. Introduction**

### **1.1 Background**

This study investigates a series of the pressurized thermal shock experiments (PTSE) performed by the Oak Ridge National Laboratory (ORNL) to provide a basis of applicability of the PTSE results to the pressurized thermal shock (PTS) evaluation of the Yankee Rowe Reactor Vessel.

The consequence of a PTS on the reactor vessel depend on factors such as material properties, transient conditions (cooling rate of the vessel and pressure transient), stresses (thermal, hoop, clad, and residual), and the size, location, and orientation of flaws in the vessel wall.

Because information about flaws in the Yankee Rowe Reactor Vessel is not available and the PTSE vessel does not have clad and residual stress data, this report examines the PTSE series from the aspects of the material properties and stresses (thermal and hoop) imposed on the vessel in comparison with the Yankee Rowe PTS analyses. Specifically, this report provides :

1. Properties of material used in the PTSE : toughness, yield and tensile strength, and the nil-ductility temperature - A comparison of these material properties among the PTSE vessel, inserts and Yankee Rowe Reactor vessel is presented in Section 2, and
2. Stress distributions and associated transient conditions in the PTSE: vessel temperature and pressure transient conditions, and thermal and hoop stress\* resulting from these transient conditions - this is presented in Section 3.1, and in Section 3.2 the transient conditions and resulting stresses for the Yankee Rowe Reactor Vessel are presented for the comparison with the PTSE results.

In Section 4, a discussion about the interpretation of the PTSE results in conjunction with the Yankee Rowe PTS evaluation will be made for experimental method, material properties, and magnitude of stress.

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\* In this report, thermal stress refers to the stress due to temperature gradient in the vessel wall, and hoop stress refers to the stress due to pressure. Because only the longitudinal flaw was investigated in the PTSE (because the longitudinal flaw is most important under PTS), both thermal and hoop stresses referred in this report are in the circumferential direction (i.e., hoop direction) so that the longitudinal flaw is subject to tensile or compressive force in the circumferential direction.

For the evaluation of the PTSE series, two reports from the ORNL, NUREG/CR-4106 [1] and NUREG/CR-4888 [2] were used. For the evaluation of the Yankee Rowe PTS transients, four representative cases developed by Yankee Atomic were utilized.

## 1.2 A Brief Description of the PTSE Series

The pressurized thermal shock experiment series in the ORNL were performed in two steps: the PTSE-1 series during December 1984 and the PTSE-2 series during November to December 1986.

In both series of the PTSE, the crack behavior was examined by monitoring a 1-m-long flaw implanted in an insert material welded into the exterior wall of the pressure vessel. In the PTSE-1 series, a high toughness material was used for the investigation of warm prestressing and the nature of crack propagation and arrest. In the PTSE-2 series, a low toughness material was used for the investigation of the crack behavior and warm prestressing with low tearing resistance.

There are three tests labeled as PTSE-1A, PTSE-1B, and PTSE-1C in the PTSE-1 series, and two tests, PTSE-2A and PTSE-2B, in the PTSE-2 series. These test cases differed from each other in the transient conditions applied to each case. In the PTSE series, the cooling was applied at the outer surface of the vessel to induce the thermal shock in contrast to the actual situation occurring in nuclear reactor PTS transients (i.e., the cooling occurs at the inside of the vessel). Fig. 1.1 illustrates temperature and stress distribution incurred in the PTSE compared with those due to an actual PTS in a nuclear reactor.

The summary of experimental observations of the PTSE series are listed in Table 1.1. Through both series of PTSE, the effect of warm prestressing was recognized, i.e., crack was observed not to propagate while  $K_I$  are decreasing even if  $K_I$  is greater than  $K_{IC}$ . Thus, the vessel rupture occurred only for PTSE-2B in which the pressure was controlled to steadily increase resulting the monotonic surge of  $K_I$  with time. More details of the transient conditions for each PTSE test will be presented in Section 3.1.



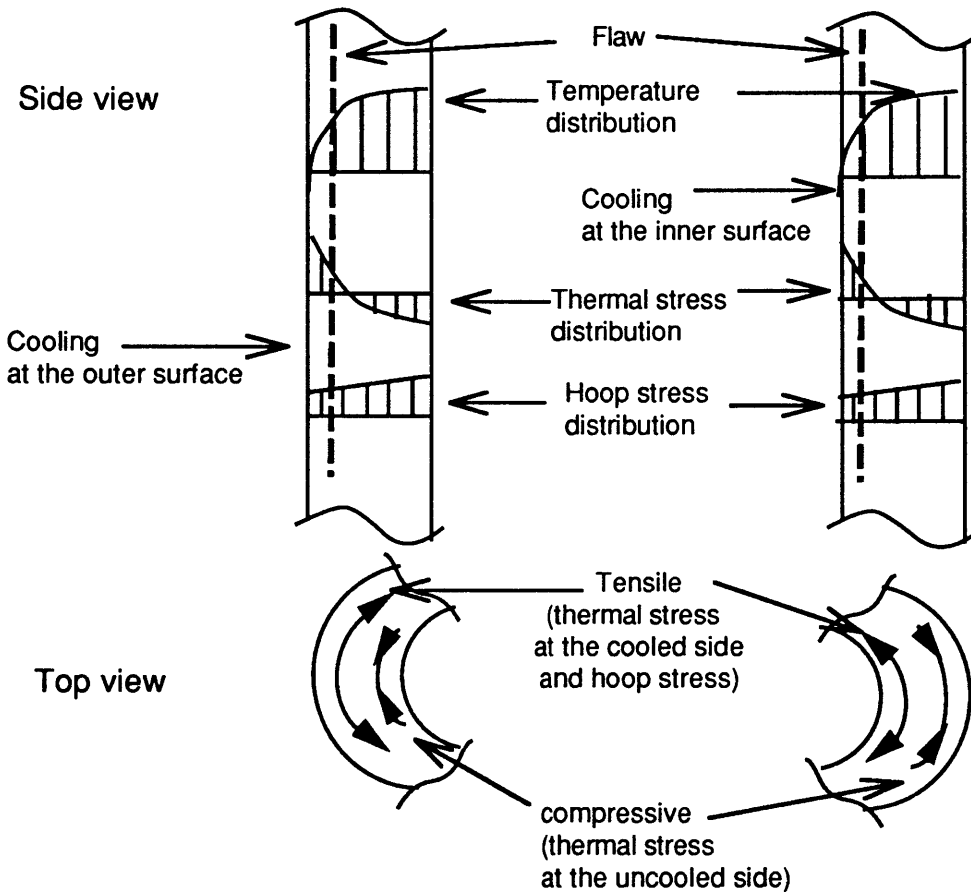
Table 1.1 Summary of experimental observations of the PTSE

Observation	PTSE-1A <sup>a</sup>	PTSE-1B <sup>a</sup>	PTSE-1C <sup>a</sup>	PTSE-2A <sup>b</sup>	PTSE-2B <sup>b</sup>
Initial Crack Depth a (inch) a/w	0.48 0.083	0.48 0.083	0.96 0.165	0.59 0.098	1.67 0.288
Final Crack Depth a (in) a/w	0.48 0.083	0.96 0.165	1.61 0.278	1.67 0.288	Rupture 1.0
Time of Crack Jump (sec) <sup>c</sup>	No Crack Propagation	67.1	125.3	249.4	420.8
Time of Maximum K <sub>I</sub> (sec) <sup>c</sup>	61 119 280.1	135.9	172	72.6 253.6	-

a: From Table 10.10 of Ref.1. In Table 10.3 of Ref.1 the initial crack depths are listed as 11.4 mm for PTSE-1A and 1B, and 22.1 mm for PTSE-1C.

b: From Table 10.10 and 9.2 of Ref.2

c: Time measured from the initiation of transients



(a) PTSE case

(b) Actual PTS case

Fig. 1.1 Temperature and stress distribution in the PTSE tests and the actual PTS in nuclear reactors

## **2. Dimensions and Material Properties**

### **2.1 PTSE Vessel**

The dimension and material property of the vessel used in the PTSE are listed in Table 2.1. The same vessel was used for both PTSE-1 and PTSE-2.

Table 2.1 Dimension and material properties of the PTSE vessel

Dimension and Property	Measured Value	Remark
Outer Radius (inch)	19.31	
Inner Radius (inch)	13.50	
Thickness (inch)	5.81	
Yield Strength (ksi)	65.27 (26 % elongation) <sup>a</sup> 62.66 (29 % elongation) <sup>a</sup>	87.02 ksi (value used for the pretest analysis) <sup>b</sup>
Tensile Strength (ksi)	84.99 (26 % elongation) <sup>a</sup> 81.66 (29 % elongation) <sup>a</sup>	
NDT (°F)	-59.8 <sup>a</sup>	

a: from Table 2.1 of Ref.1. The  $RT_{NDT}$  is not defined for the vessel material

b: from Table 10.8 of Ref.1

## 2.2 PTSE Inserts

Table 2.2 shows the material properties\* of the insert for the PTSE-1 series. The stress - strain for the PTSE-1 insert is shown in Fig.2.1. The  $K_{IC}$  and  $K_{IA}$  data and curves for the PTSE-1 insert are shown in Fig.2.2 and 2.3 respectively.

Table 2.2 Material properties of the insert in PTSE-1

Property	Measured Value	Remark
Yield Strength (ksi)	$[92.78 - 0.046 (T-32) + 7.315 \times 10^{-5}(T-32)^2]^a$ (T in °F)	87.02 (value used for the pretest analysis) <sup>b</sup>
Tensile Strength (ksi)	$[116.73 - 3.543 \times 10^{-4}(T-32) + 9.568 \times 10^{-5}(T-32)^2]^a$ (T in °F)	
$RT_{NDT}$ (°F)	196.3 <sup>c</sup>	

a: From Table 2.3 of Ref.1

b: From Table 10.2 of Ref.1

c: From Section 2.3.3 (page 18) of Ref.1

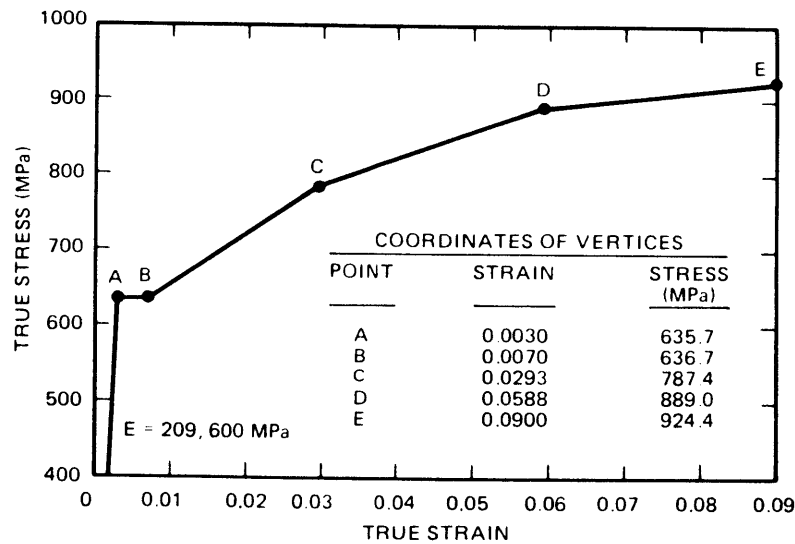


Fig.2.1 Piecewise linear stress-strain relationship used for the pretest analysis of PTSE-1 (source from Fig.10.18 of Ref.1)

\* In Ref.1 it is not mentioned whether the material properties of the insert are of those examined before or after the tests.

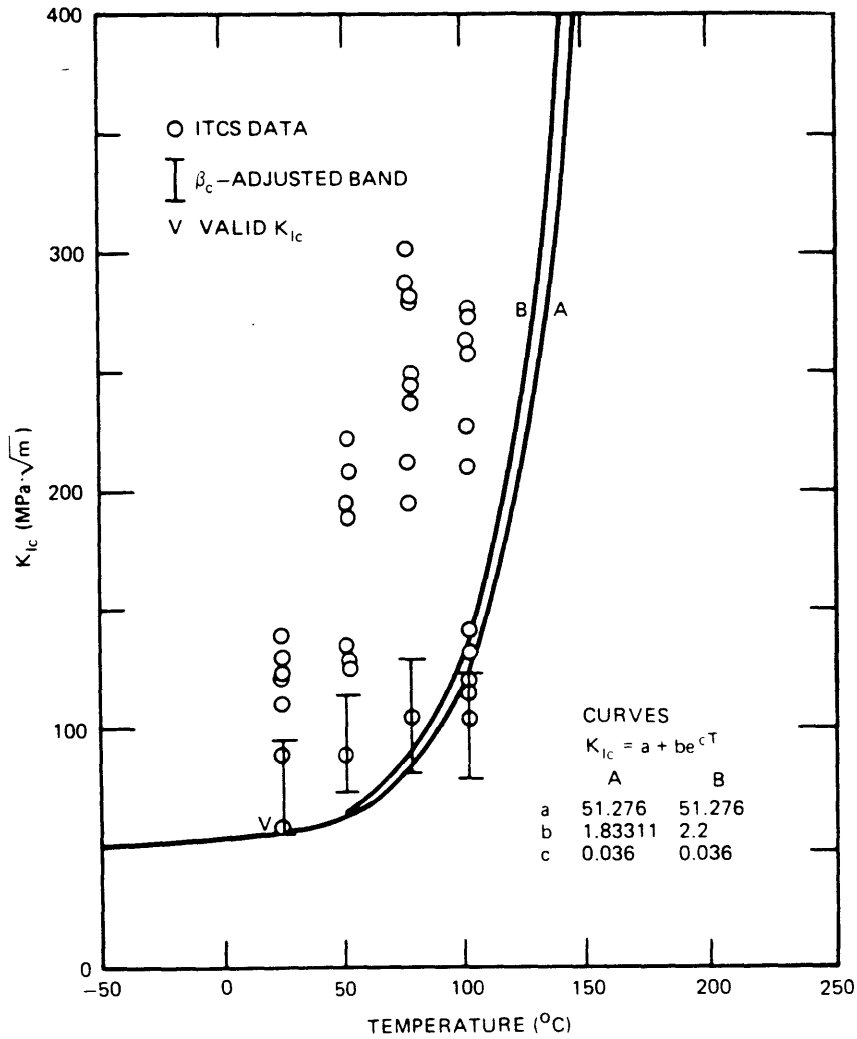


Fig.2.2 K<sub>IC</sub> data for PTSE-1.\* Curves represent functions in the pretest analysis. (source from Fig.10.16 of Ref.1)

\* The original figure caption(Fig.10.16 of Ref.1) reads " K<sub>IC</sub> for PTSE-1 vessel". However, it is believed that the data shown in Fig 2.2 are for the PTSE-1 insert because the pretest analysis was performed for the insert material..

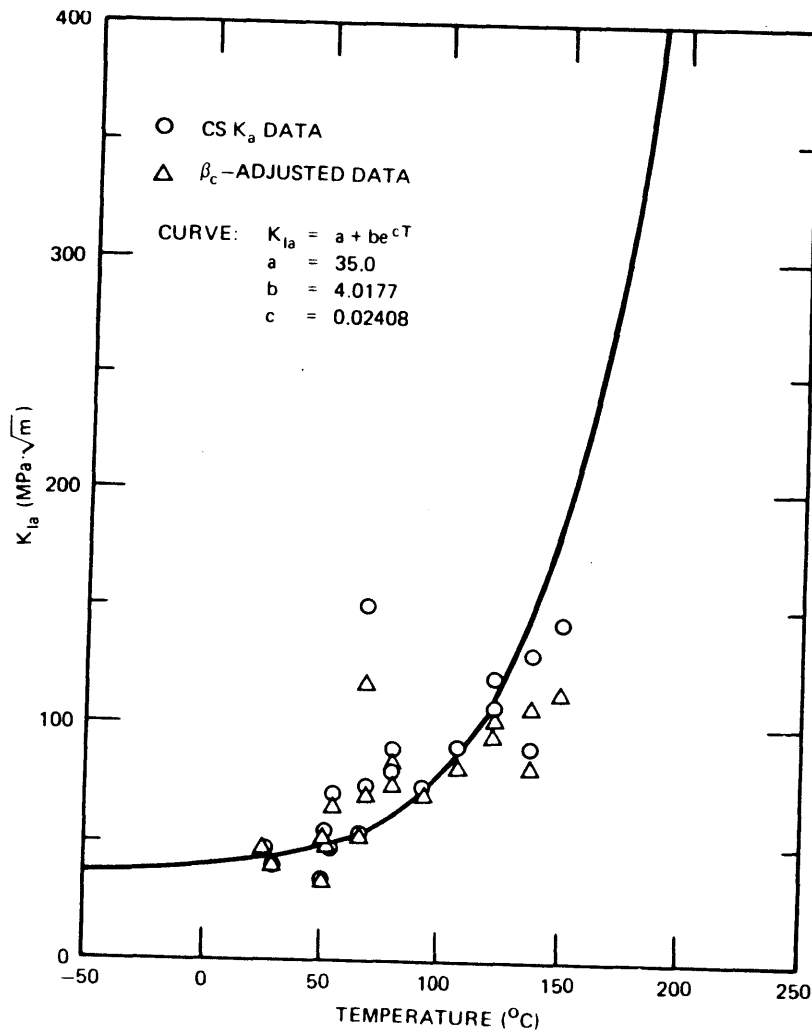


Fig.2.3  $K_{IA}$  data for PTSE-1.\* Curve represents function in the pretest analysis (source from Fig.10.17 of Ref.1)

\* The original figure caption(Fig.10.16 of Ref.1) reads "  $K_{IA}$  for PTSE-1 vessel". However, it is believed that the data shown in Fig 2.2 are for the PTSE-1 insert because the pretest analysis was performed for the insert material..

In the PTSE-2 series the material properties of the insert were examined before and after the experiments. Some changes of material properties were observed before and after the experiments possibly because of plastic deformation incurred during the tests. However, Ref.2 mentions that the change of material properties due to plastic deformation is not so conclusive because a regional variation of material properties were observed on the piece of metal from which the insert and specimen were cut. We introduce both results of material examination before and after the tests. Table 2.3 are those obtained from the examination prior to the tests. Figs. 2.4, 2.5, and 2.6 show the stress - strain relation,  $K_{IC}$ , and  $K_{IA}$  curves obtained from the pretest specimen respectively.

Table 2.3 Pretest material properties of the insert in PTSE-2

Property	Temperature (°F)				Value used for the pretest analysis <sup>d</sup>
	78.8	212	392	550.4	
Yield Strength <sup>a</sup> (ksi)	38.94	32.85	28.86	29.88	36.98
Tensile Strength <sup>a</sup> (ksi)	80.06	69.04	62.95	63.74	75.13
NDT <sup>b</sup> (°F)	120.2				
RT <sub>NDT</sub> <sup>c</sup> (°F)	210.2				

a: Averaged value at a given temperature. See Table 2.6 of Ref.2 for the individual data

b: From Table 2.4 of Ref.2

c: From Section 2.3.5 (page 53) of Ref.2

d: From Table 10.4 of Ref.2

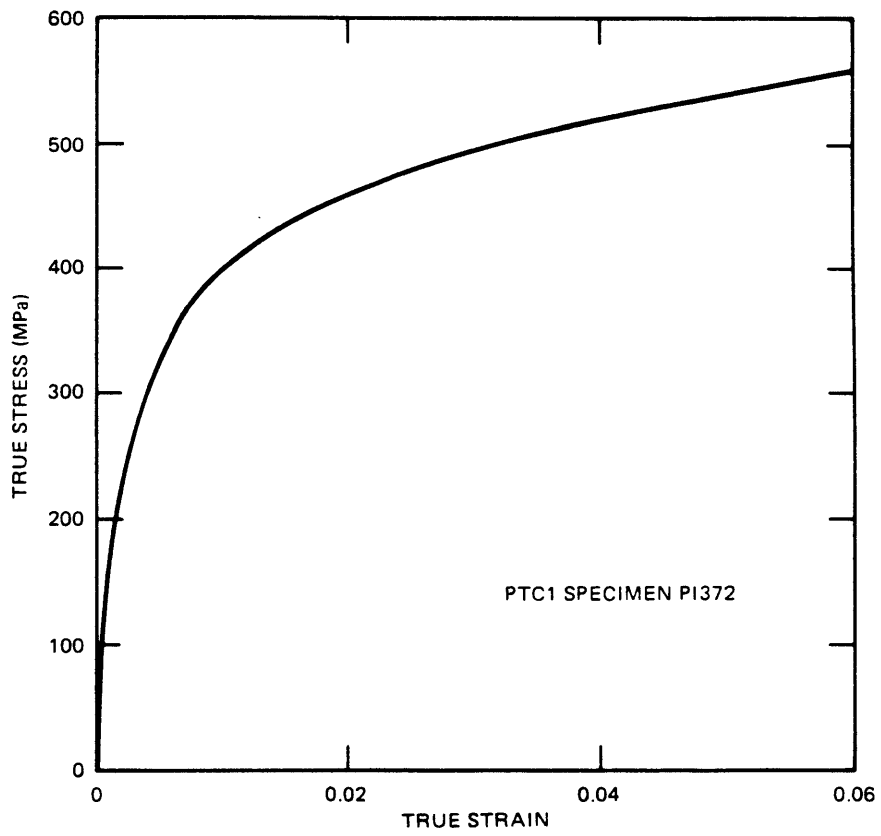


Fig.2.4 True stress vs. strain from tensile test of specimen (pretest material) at 212 °F.  
(source from Fig.2.24 of Ref.2)

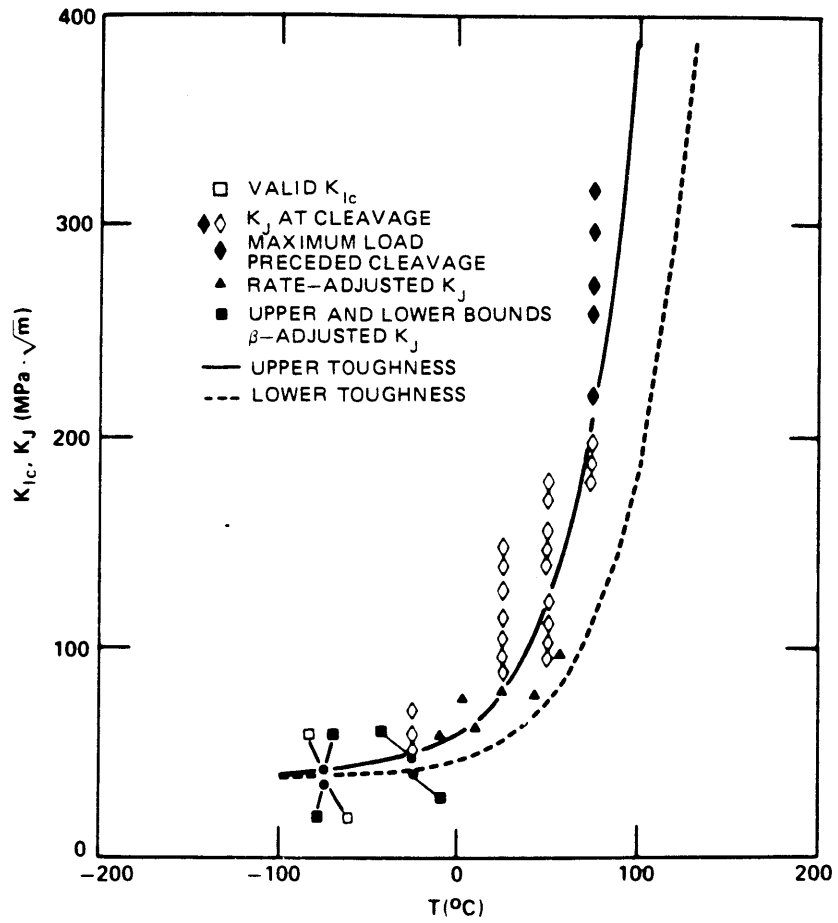


Fig.2.5  $K_{IC}$  data for PTSE-2 insert (pretest). (source from Fig.10.10 of Ref.2)



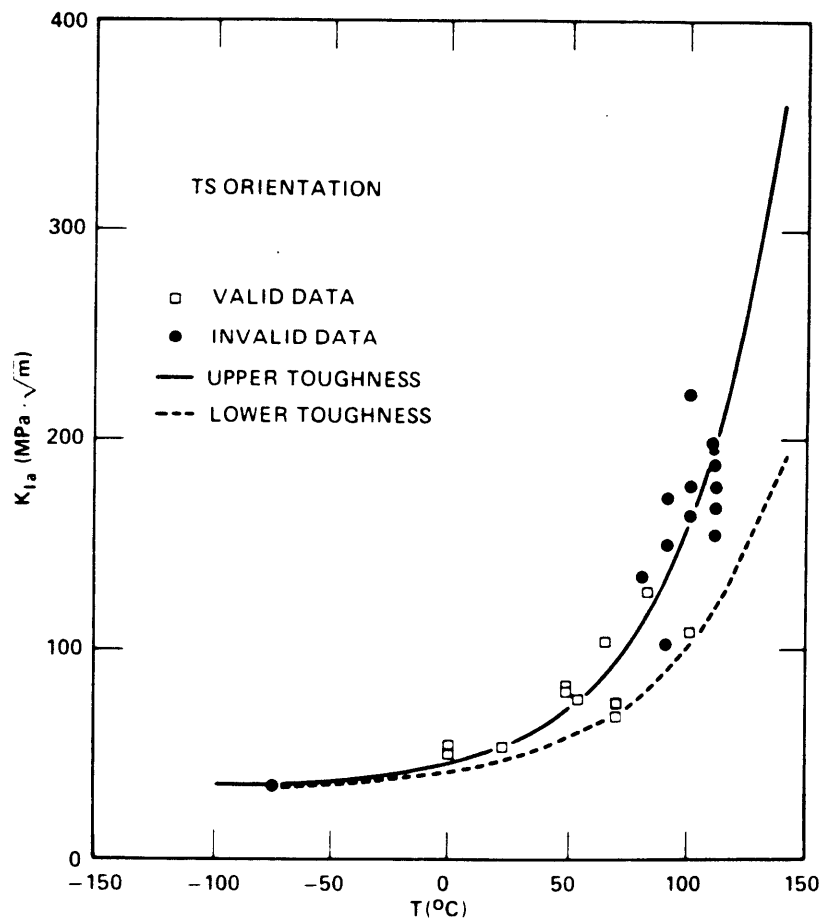


Fig.2.6  $K_{IA}$  data for PTSE-2 insert (pretest). (source from Fig.10.9 of Ref.2)

Table 2.4 shows the material properties of the insert after the PTSE-2. The stress - strain curve obtained from the post test examination is shown in Fig.2.7. Fig.2.8 shows the  $K_{JC}$  of the insert examined after the experiments compared with the pretest data obtained from the specimen of the material of which the insert was made. It is observed from Fig.2.8 that the toughness of the insert material decreases after the experiment. As noticed from Table 2.3 and 2.4, the nil-ductility temperature (NDT) increased after the experiments. However, the reference nil-ductility temperature ( $RT_{NDT}$ ) could not be defined for the post-test insert, because the insert did not achieve 68 J on the upper shelf ( see Section 2.3.5 (page 53) of Ref.2 for details).

Table 2.4 Post-test material properties of the insert in PTSE-2

Property	Temperature (°F)		
	77	212	392
Yield Strength <sup>a</sup> (ksi) (T oriented)	67.70	63.45	60.92
Yield Strength <sup>b</sup> (ksi) (L oriented)	53.81	55.33	-
Tensile Strength <sup>a</sup> (ksi) (T oriented)	90.33	83.7	78.97
Tensile Strength <sup>b</sup> (ksi) (L oriented)	89.78	80.13	-
NDT <sup>c</sup> (°F)	167		

a: Averaged value at a given temperature. See Table 2.7 of Ref.2 for the individual data

b: Averaged value at a given temperature. See Table 2.8 of Ref.2 for the individual data

c: From Table 2.4 of Ref.2

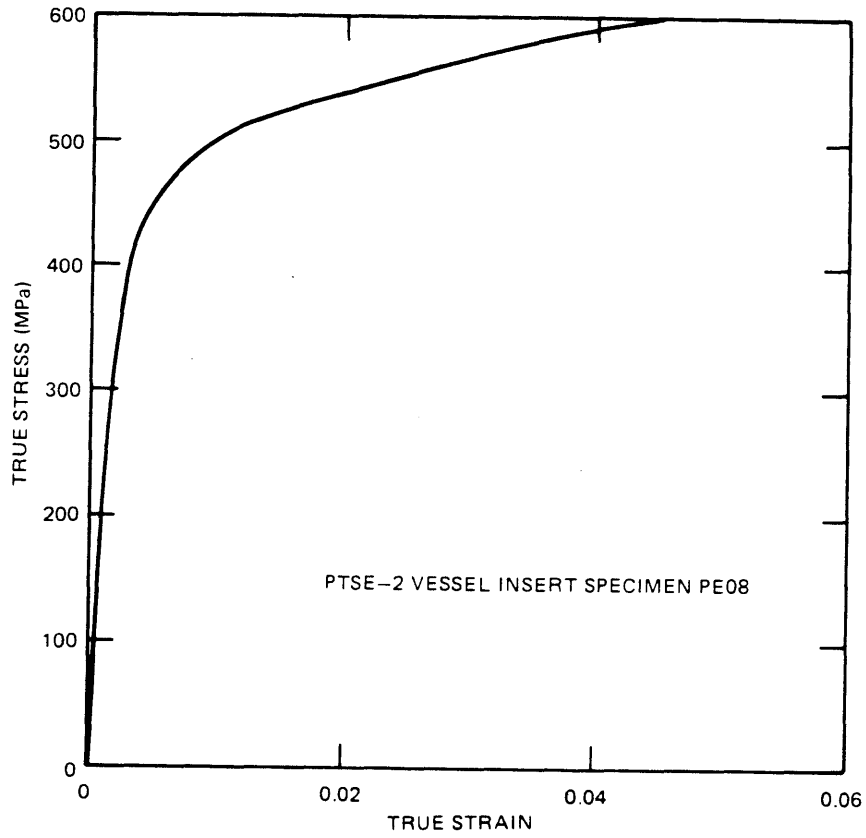


Fig.2.7 True stress vs. strain from tensile test of specimen (posttest material) at 212 °F. (source from Fig.2.25 of Ref.2)

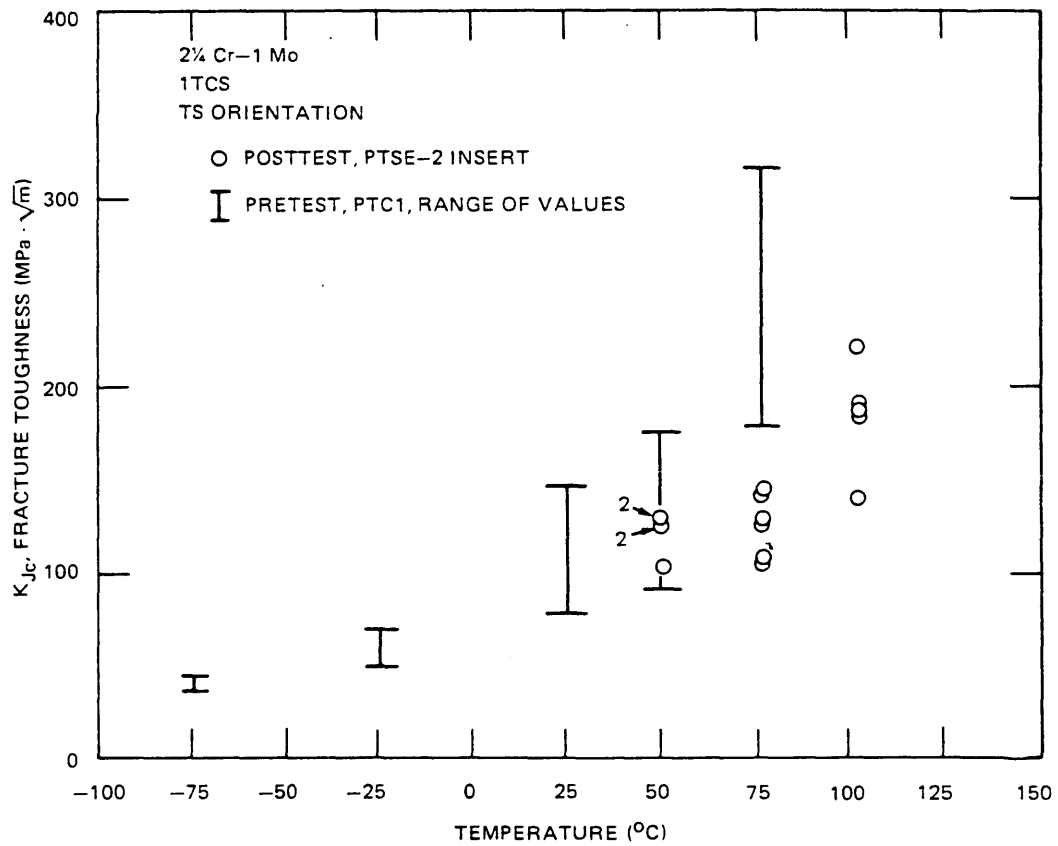


Fig.2.8 Posttest fracture toughness  $K_{Jc}$  for PTSE-2 insert compared with similar pretest specimens. (source from Fig.2.52 of Ref.2)

### 2.3 Yankee Rowe Reactor Vessel

The dimension and material properties of the Yankee Rowe Reactor Vessel are listed in Table 2.5. The values of yield and tensile strength are of the unirradiated vessel metal. The properties of the irradiated vessel are not available.

Table 2.5 Dimension and material properties of the Yankee Rowe Reactor Vessel Plate material

Dimension and Property	Value
Outer Radius (inch)	54.5
Inner Radius (inch)	62.375
Thickness (inch)	7.875
Yield Strength (ksi)	53 - 68 (unirradiated)
Tensile Strength (ksi)	86 - 93 (unirradiated)
Initial RT <sub>NDT</sub> (°F)	30
Irradiated RT <sub>NDT</sub> (°F)	275 - 350 (estimated)

### **3. PTS Transients and Stress Distributions**

A total of nine PTS transients were investigated: all five cases of the PTSE series and four cases for the Yankee Rowe PTS analyses. For the stress field calculation, the VISAY code was used. The VISAY code is a modified version of VISA-IID which was originally developed in the Battell Pacific Northwest Laboratory [3].

#### **3.1 PTSE series**

The VISAY code requires three types of thermal hydraulic transient data to calculate the stress and analyze the PTS on a vessel. They are the coolant temperature, pressure, and heat transfer coefficient ( $h_c$ ) on the surface of a vessel. However, Refs 1 and 2 do not contain the coolant temperature history nor the heat transfer coefficient values measured from the actual tests. In order to have the code calculate temperature and stress field, therefore, we trick the VISAY code by putting the surface temperature data as the coolant temperature and assuming a constant value of the  $h_c$ . The assumed value of the  $h_c$  is  $10^4$  BTU/hr ft<sup>2</sup> which is a value reasonably enough to neglect the temperature difference between the coolant and surface of the vessel. Thus, the vessel surface temperature calculated in the VISAY code can be equivalent to the actual surface temperature. This assumption of using the surface temperature as coolant temperature with the  $h_c$  of  $10^4$  BTU/hr ft<sup>2</sup> was checked through the sensitivity analysis of the maximum stress on the variation of the  $h_c$ . Table 3.1 shows the change of thermal stress due to the variation of the assumed value of  $h_c$ . The thermal stress with the  $h_c$  of  $10^6$  BTU/hr ft<sup>2</sup> is slightly higher than with the  $h_c$  of  $10^4$  because the cooling rate at the surface is faster for higher  $h_c$  resulting larger temperature gradient within the vessel wall. However, the change of thermal stress is noticed to be less than 3 % although the value of  $h_c$  changed 100 times. Therefore, it is concluded that the method of modeling the PTSE for the VISAY code is acceptable.

Table 3.1 The maximum thermal stress calculated by VISAY with different values of  $h_c$

Case	Time (min)	Max. thermal stress with $h_c=10^4$	Max. thermal stress with $h_c=10^6$
PTSE-2A	0.87	106.2 (ksi)	108.8 (ksi)
	1.30	111.4	113.4
	1.73	111.6	113.1
	2.16	109.9	111.1
PTSE-2B	0.7	87.7	90.0
	1.4	98.2	99.8
	2.1	97.9	99.1
	6.99	72.9	73.2

Note: the unit of  $h_c$  is BTU/hr ft<sup>2</sup>.

Table 3.2 lists the sources of the pressure and vessel surface temperature data used for the stress calculation using VISAY code.

Table 3.2 Sources of the pressure and temperature data for PTSE stress calculations

Case	Vessel Surface Temperature	Pressure
PTSE-1A	Appendix A of Ref.1	Fig.10.21 of Ref.1
PTSE-1B	Appendix A of Ref.1	Fig.10.34 of Ref.1
PTSE-1C	Appendix A and Fig.8.7 of Ref.1	Fig.8.8 of Ref.1
PTSE-2A	Appendix A.1 of Ref.2	Table 10.11 of Ref.2
PTSE-2B	Appendix A.2 of Ref.2	Table 10.11 of Ref.2

The PTS transient conditions and resulting stress fields calculated by VISAY are shown in Figs 3.1a through 3.5e. Figs.3.1a to 3.1e are for PTSE-1A, Figs.3.2a to 3.2e are for PTSE-1B, Figs.3.3a to 3.3e are for PTSE-1C, Figs.3.4a to 3.4e are for PTSE-2A, and Figs.3.5a to 3.5e are for PTSE-2B. The plotted data shown in Fig.3.1a through 3.5e are pressure and vessel surface temperature transients, temperature distributions within the vessel wall, thermal, hoop, and total stresses for each case.

In the PTSE series, cooling occurred at the outer wall of the vessel. The origin of the abscissa in the figures for the stress fields and temperature profiles in the vessel wall is the outer wall of the vessel as marked in the figures.

For the stress calculations of the PTSE series, we assumed zero residual stress. Since the vessel used for the PTSE does not have clad and zero residual stress was assumed, the total stress is simply the sum of the thermal and hoop stresses.



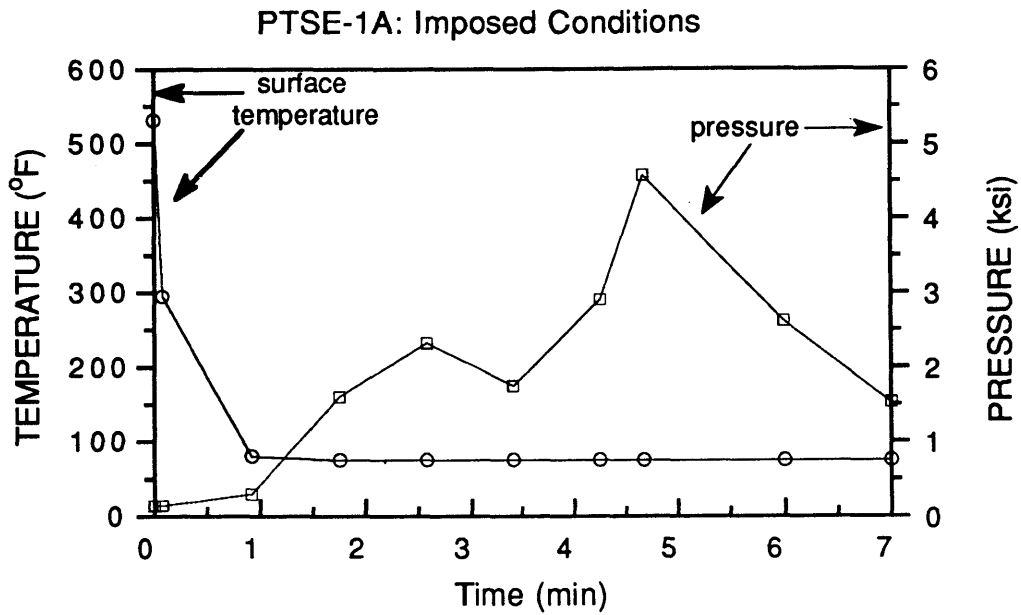
### 3.2 Yankee Rowe PTS Transients

Four cases were analyzed for the PTS transients of the Yankee Rowe Reactor Vessel: one case for the small break loss of coolant accident labeled as SBLOCA (Case 170) and three cases for the main steam line break labeled as MSLB (Case 971), MSLB (Case 973), and MSLB (Case 974) respectively. The transient input data for VISAY (coolant temperature, pressure, heat transfer coefficient) were provided from the thermal hydraulic analyses of these four cases developed by Yankee Atomic.

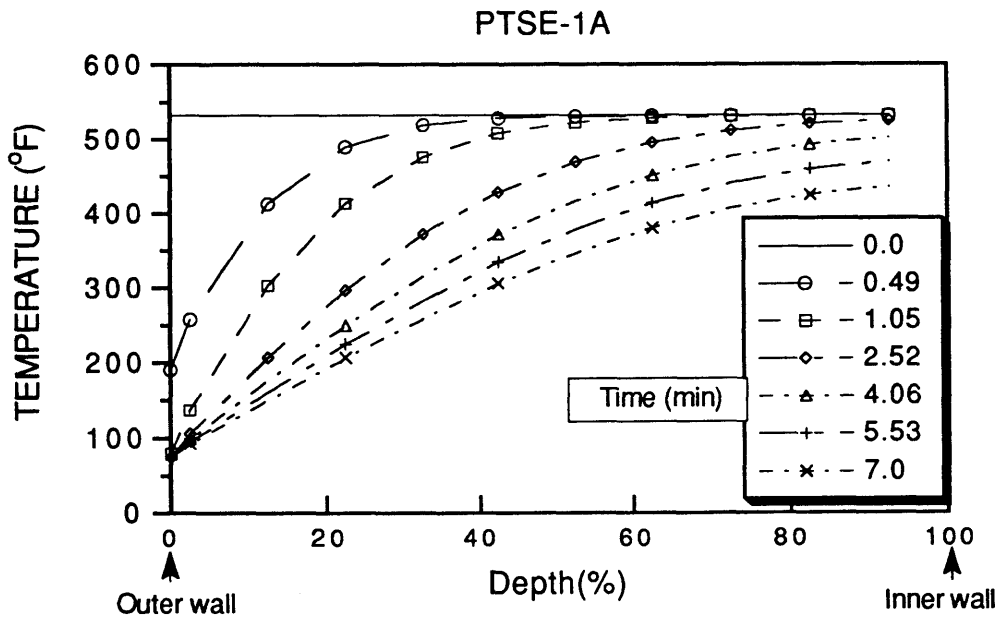
Figs. 3.6a to 3.9f show the transient conditions and resulting stress fields for these four cases: Figs. 3.6a to 3.6f for SBLOCA (Case 170), Figs. 3.7a to 3.7f for MSLB (Case 971), Figs. 3.8a to 3.8f for MSLB (Case 973), and Figs. 3.9a to 3.9f for MSLB (Case 974). The plotted data shown in Fig. 3.6a to 3.9f are pressure and vessel surface temperature transients, heat transfer coefficient on the surface of the vessel, temperature distributions within the vessel wall, thermal, hoop, and total stresses for each case.

Since cooling occurs at the inside of the reactor vessel, the origin of the the abscissa in the figures for the stress fields and temperature profiles in the vessel wall is the inner wall of the vessel as marked in the figures.

The total stress shown in Figs. 3.6f, 3.7f, 3.8f and 3.9f is the sum of thermal, hoop, residual, and clad stress. The maximum residual stress given as an input is 8 ksi. The clad of the Yankee Rowe Reactor Vessel is 0.25 inch thick (3 % of the vessel wall thickness). The maximum clad stress was calculated to be 23 to 27 ksi for the investigated transients. As noticed in the total stress figures, the stress level drops at the depth of 3 % (the interface between the clad and vessel) due to the clad. Thus, the maximum total stress within the vessel wall which occurs at the surface of the vessel wall (i.e., the interface between the clad and the vessel wall) was calculated to be 69.4 ksi for MSLB (Case 971).

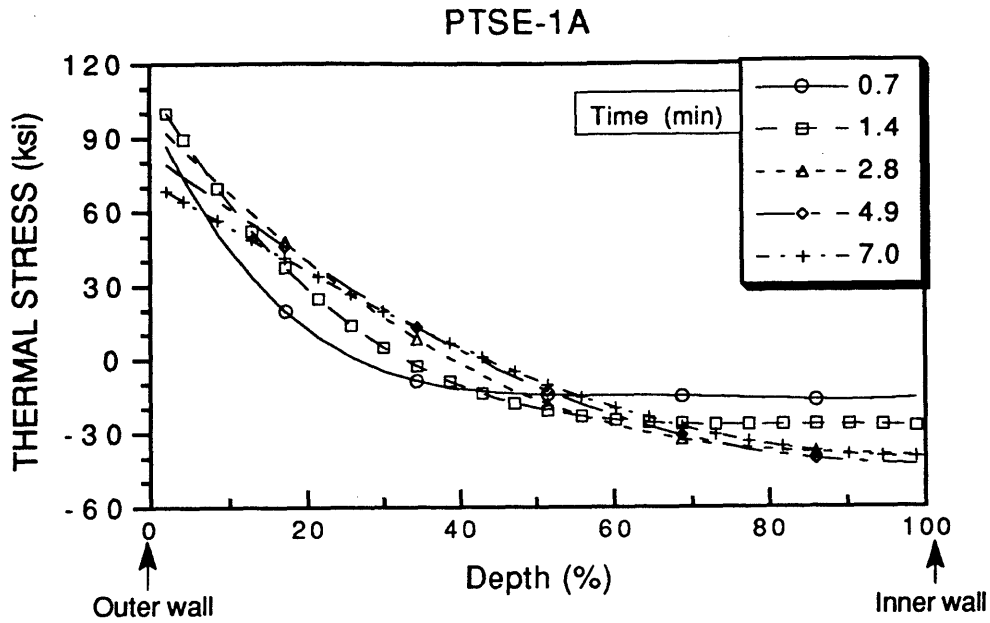


(a) Transient conditions

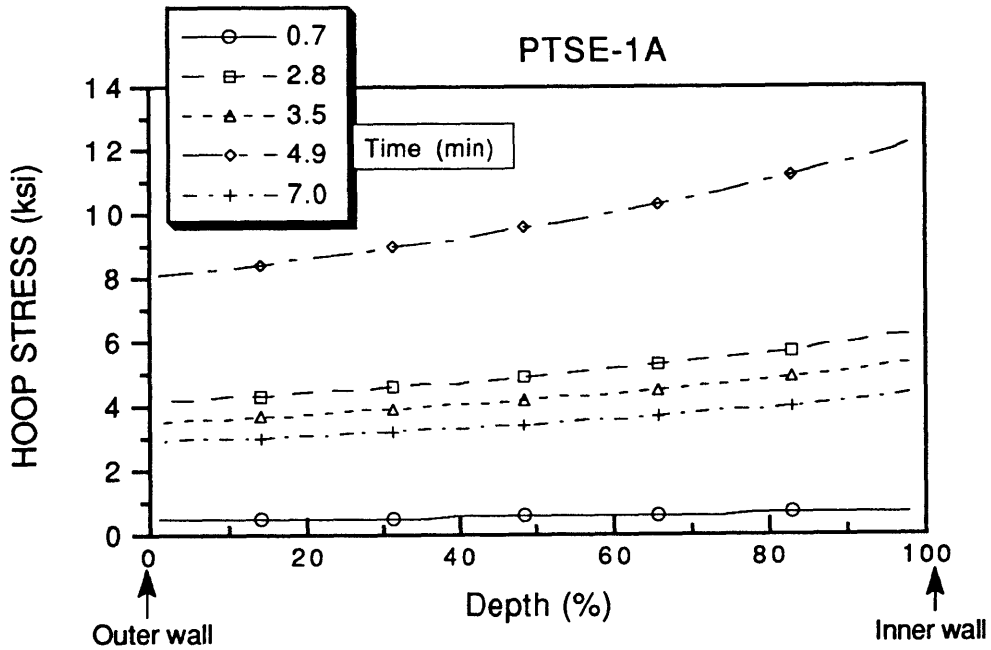


(b) Temperature distribution within the vessel wall

Fig. 3.1 Transient conditions and stress distributions in PTSE-1A

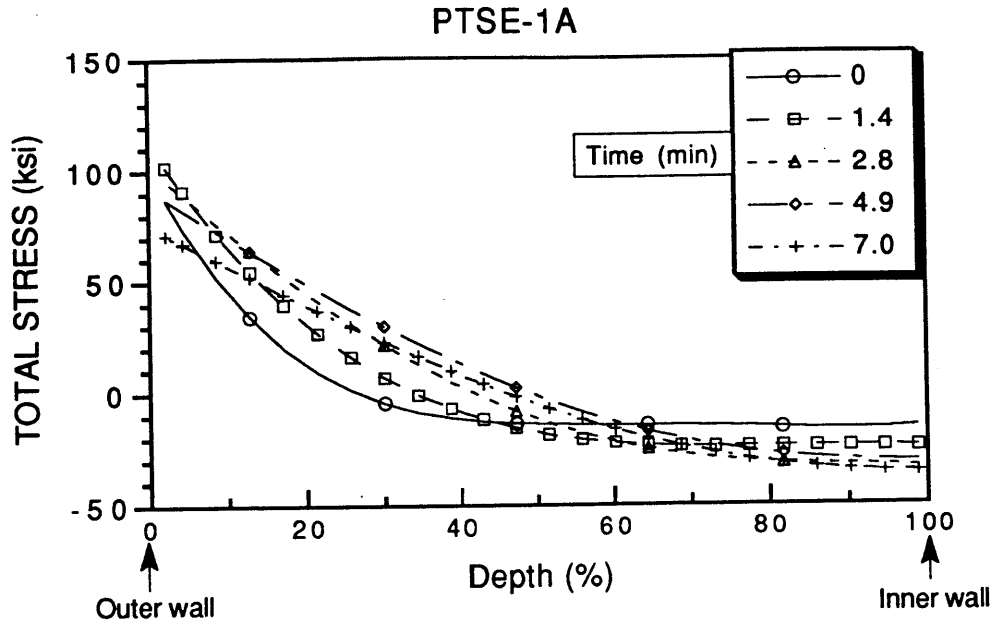


(c) Thermal stress distribution



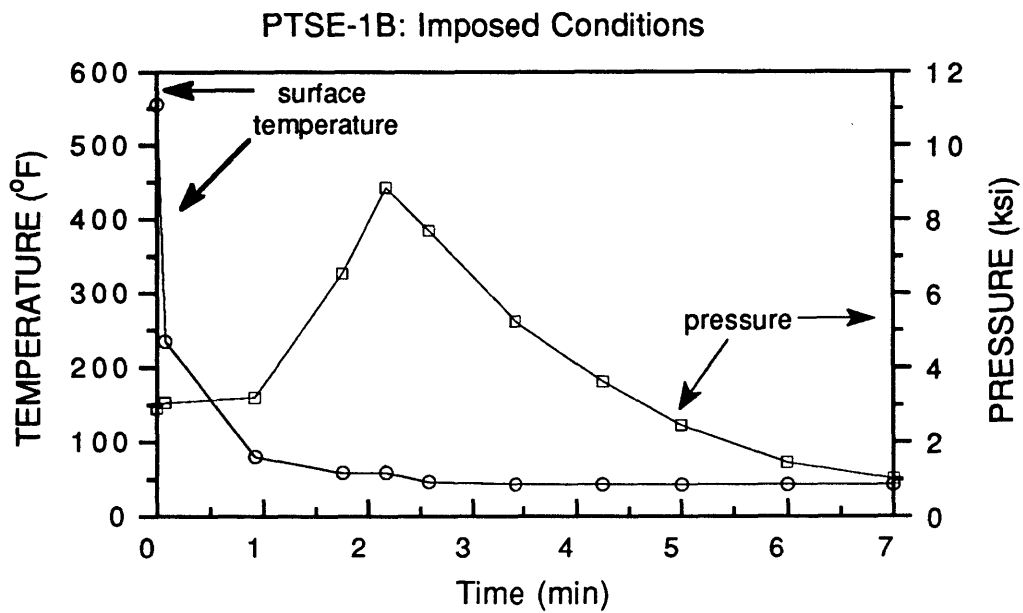
(d) Hoop stress distribution

Fig.3.1 continued from the previous page

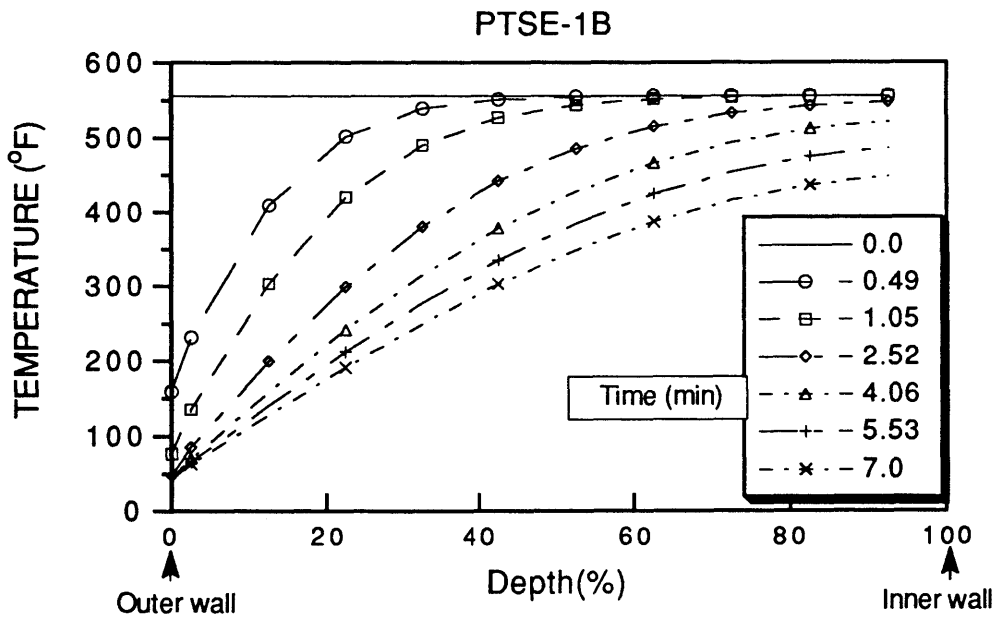


(e) Total stress distribution

Fig.3.1 continued from the previous page



(a) Transient conditions



(b) Temperature distribution within the vessel wall

Fig. 3.2 Transient conditions and stress distributions in PTSE-1B

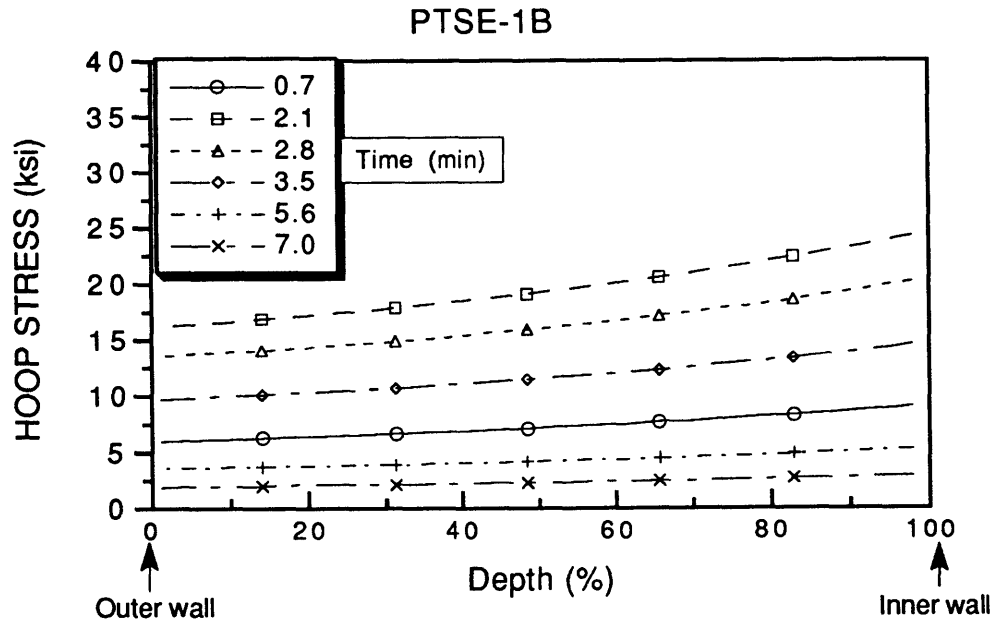
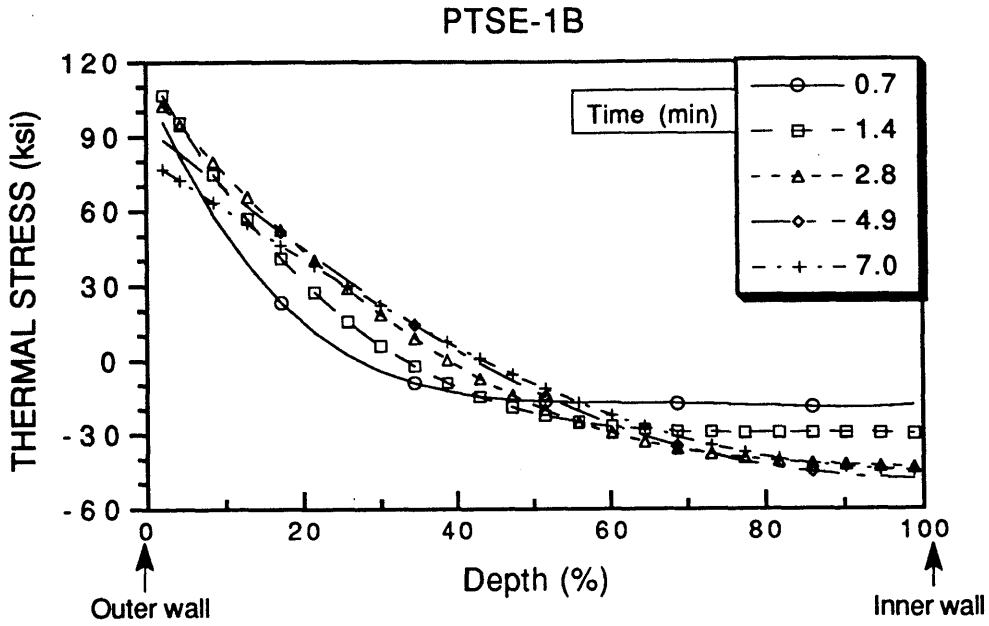
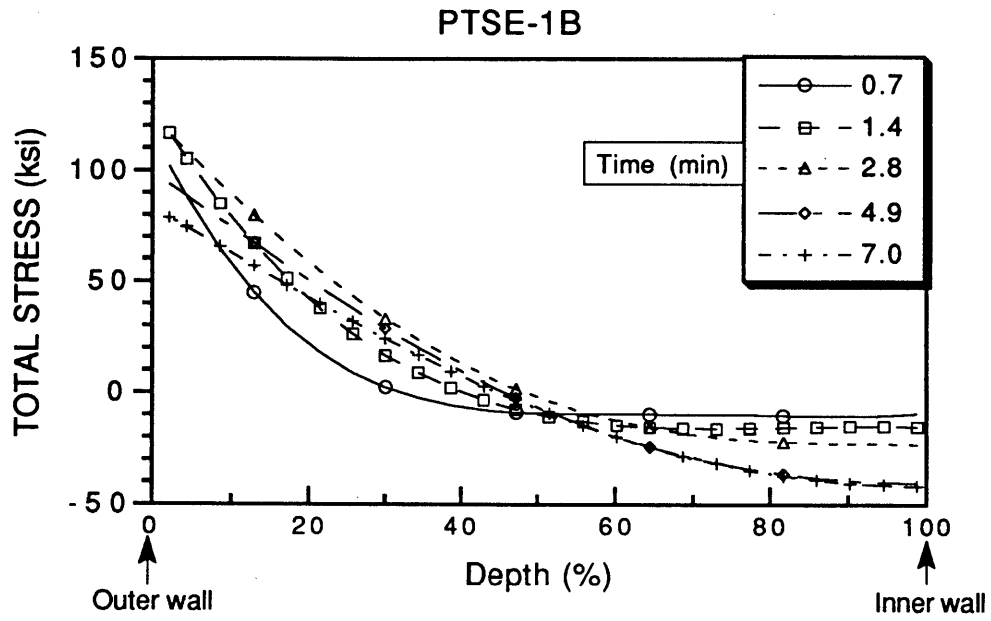
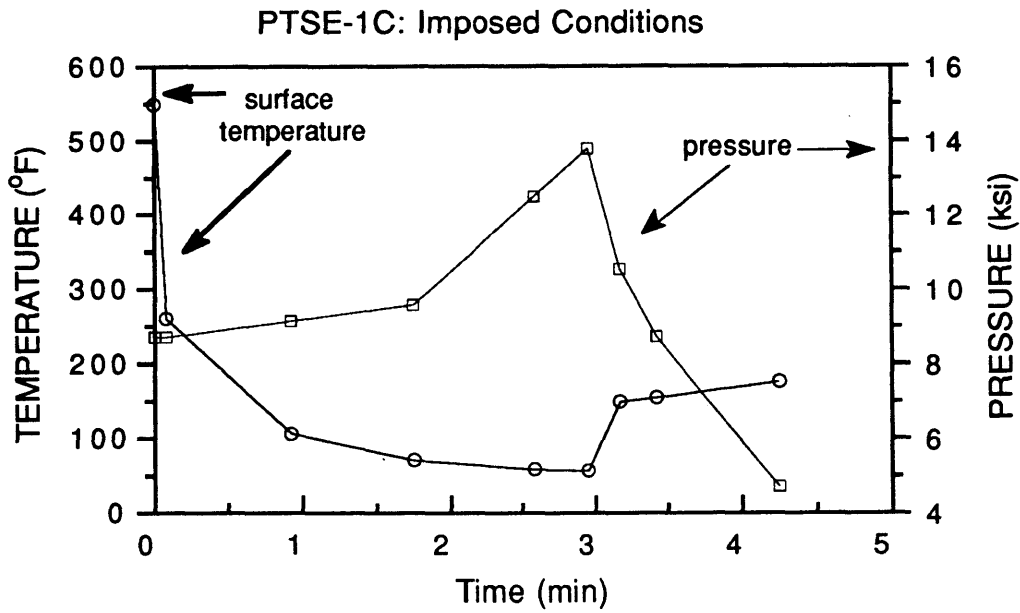


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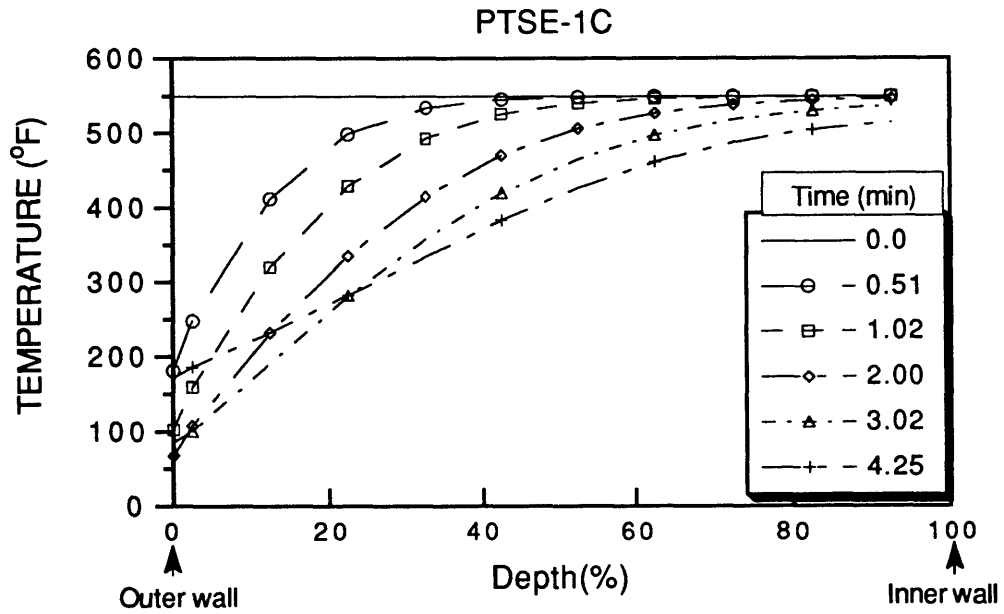


(e) Total stress distribution

Fig.3.2 continued from the previous page



(a) Transient conditions



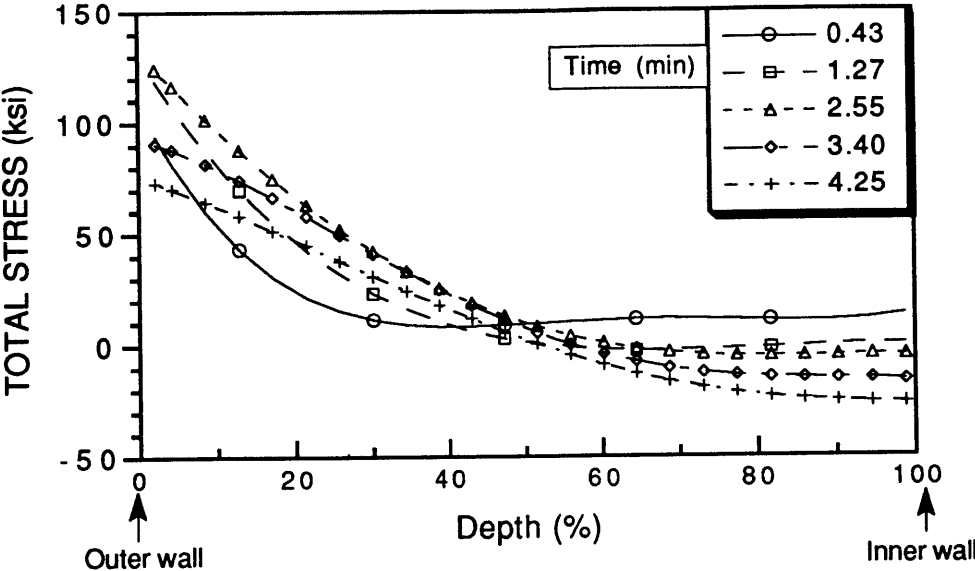
(b) Temperature distribution within the vessel wall

Fig. 3.3 Transient conditions and stress distributions in PTSE-1C



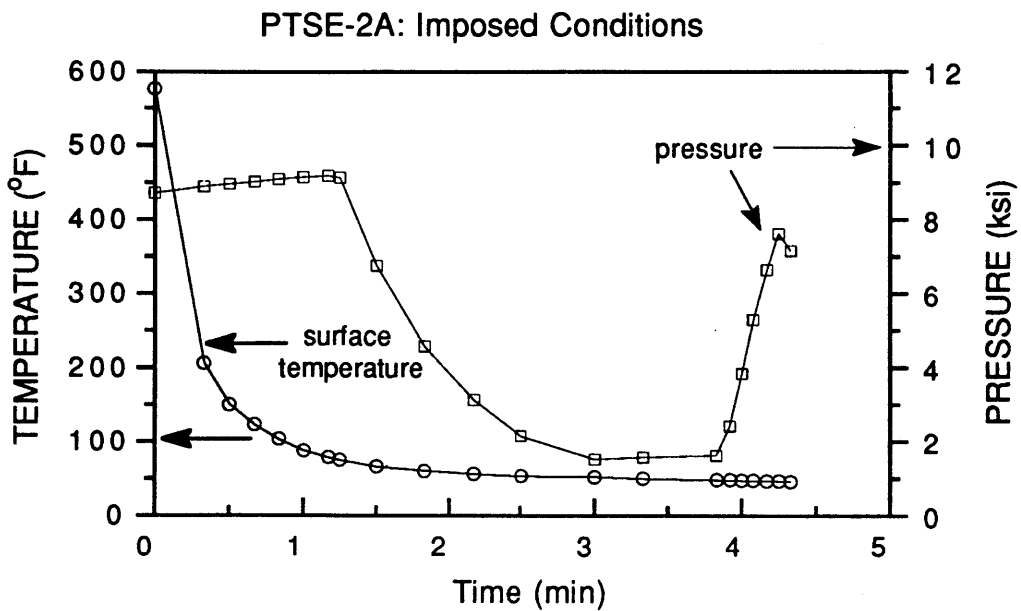


PTSE-1C

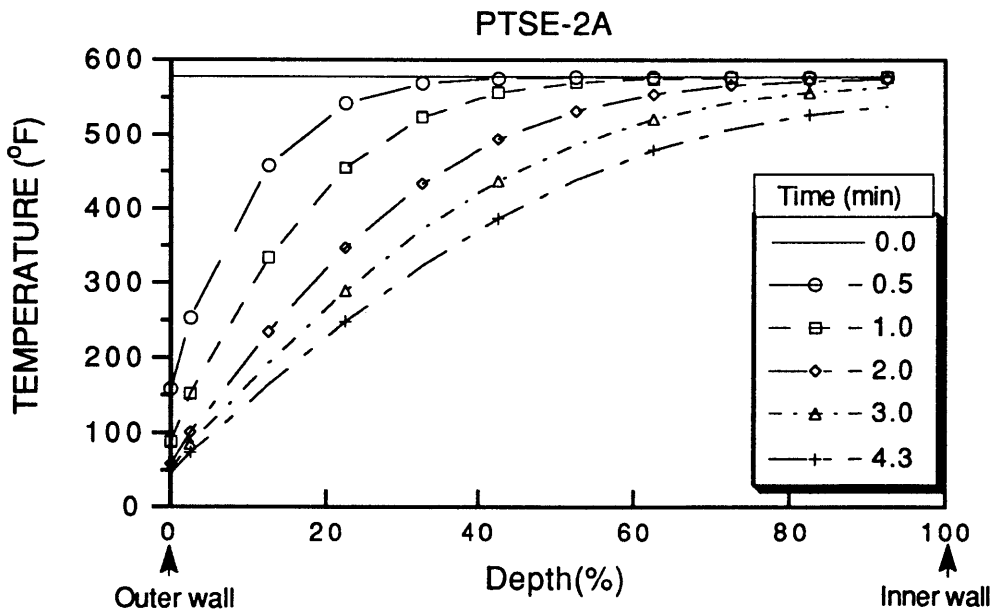


(e) Total stress distribution

Fig.3.3 continued from the previous page



(a) Transient conditions



(b) Temperature distribution within the vessel wall

Fig. 3.4 Transient conditions and stress distributions in PTSE-2A

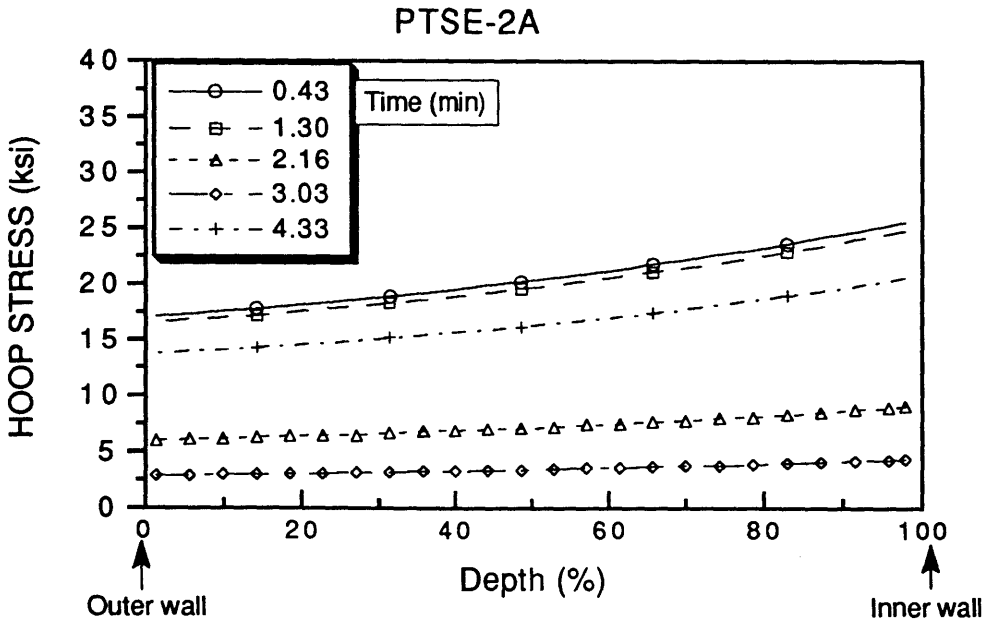
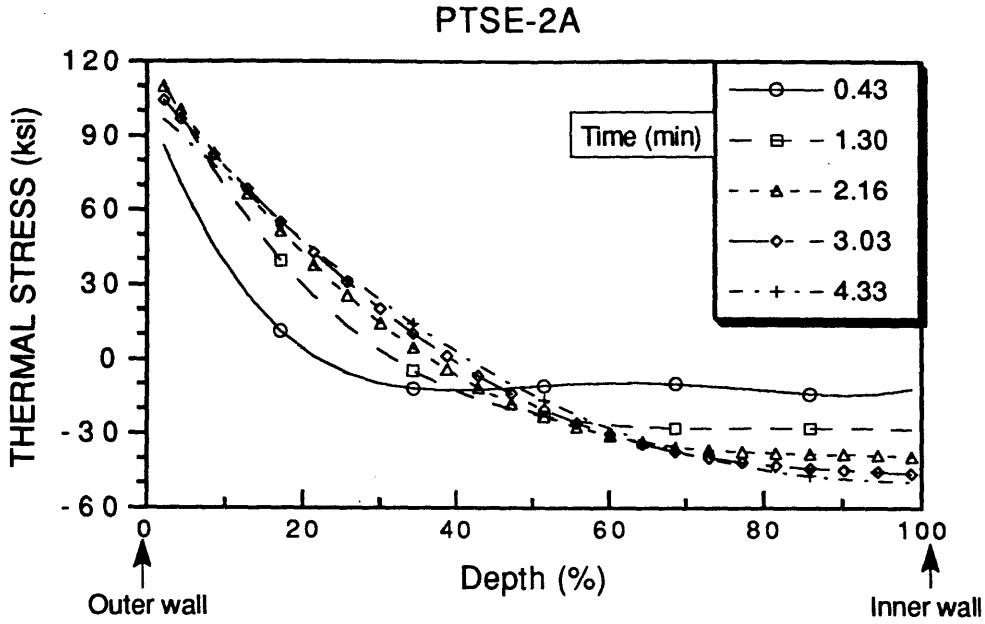
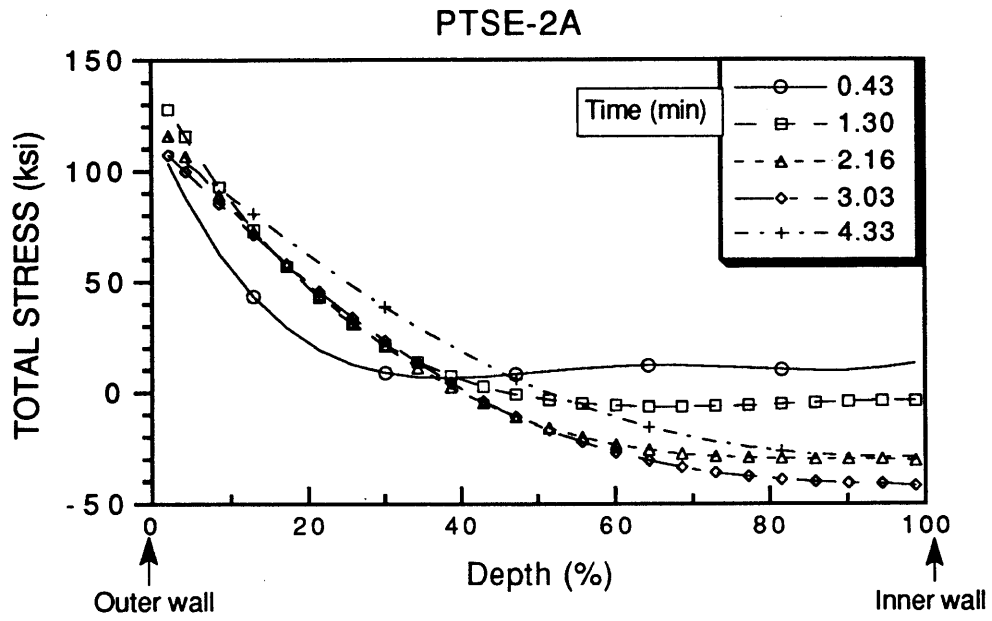
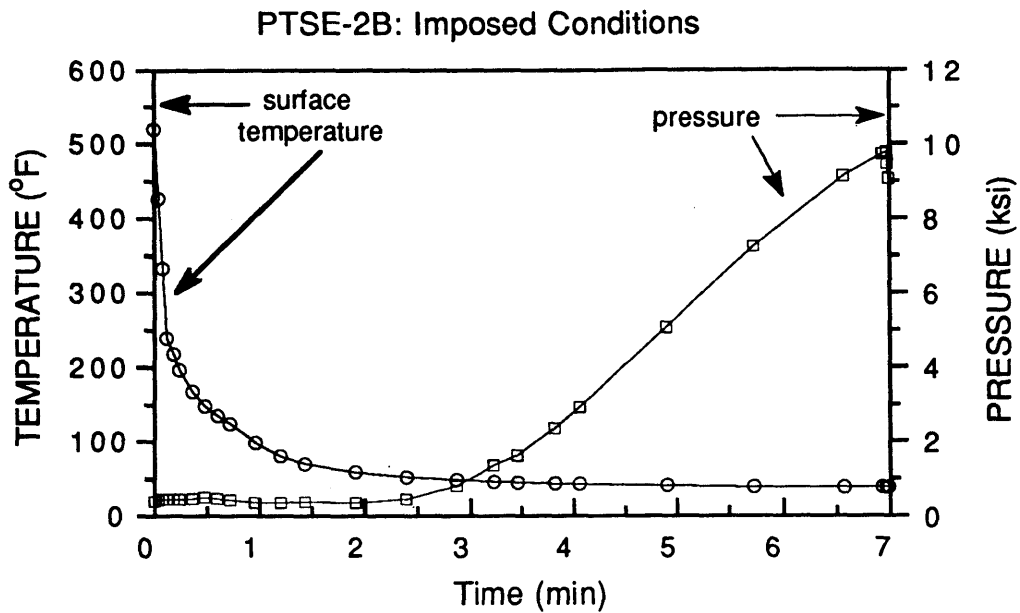


Fig.3.4 continued from the previous page

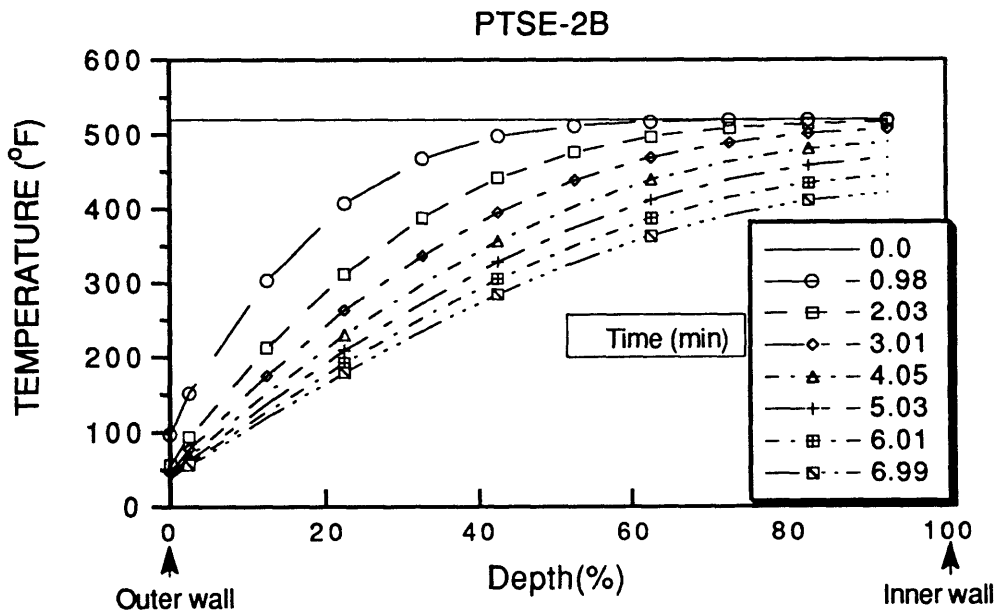


(e) Total stress distribution

Fig.3.4 continued from the previous page



(a) Transient conditions



(b) Temperature distribution within the vessel wall

Fig. 3.5 Transient conditions and stress distributions in PTSE-2B

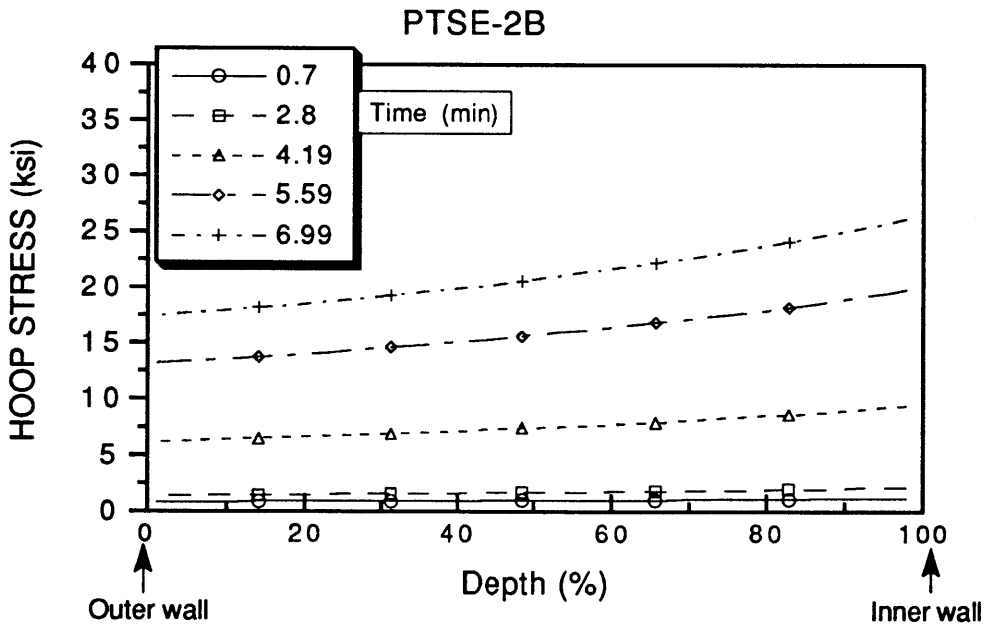
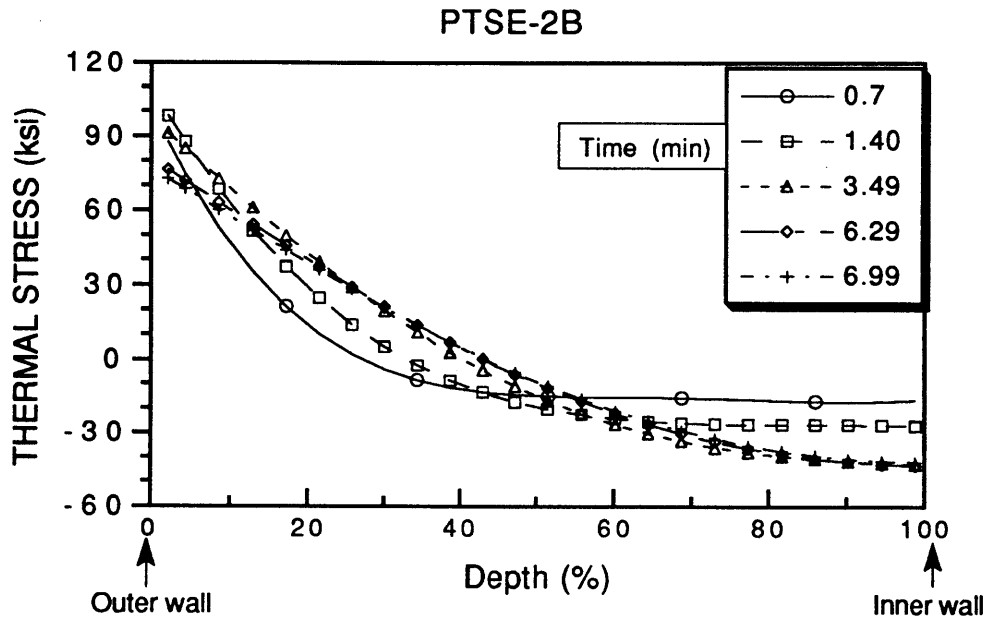
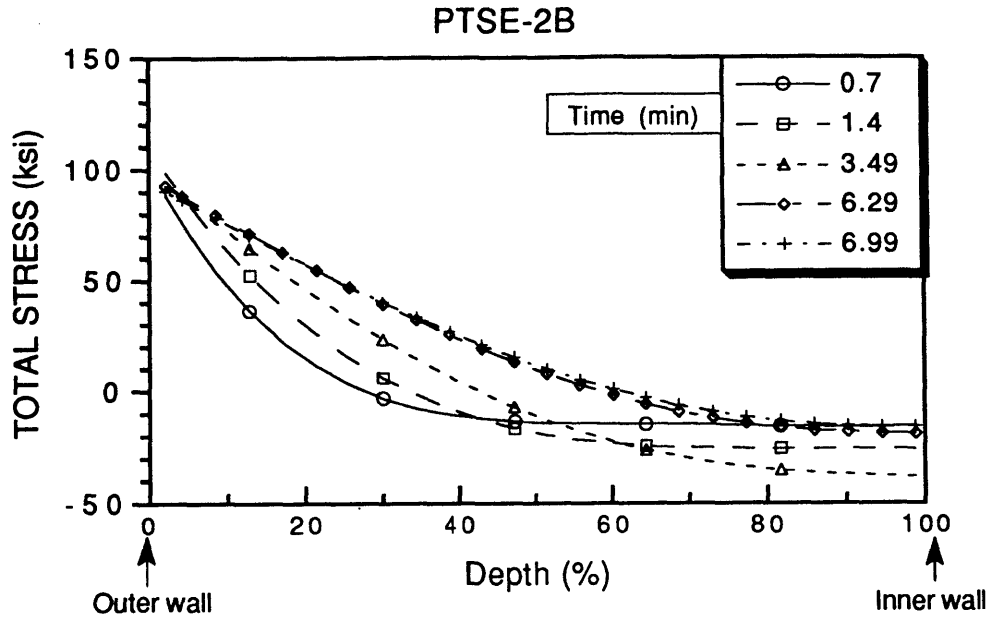


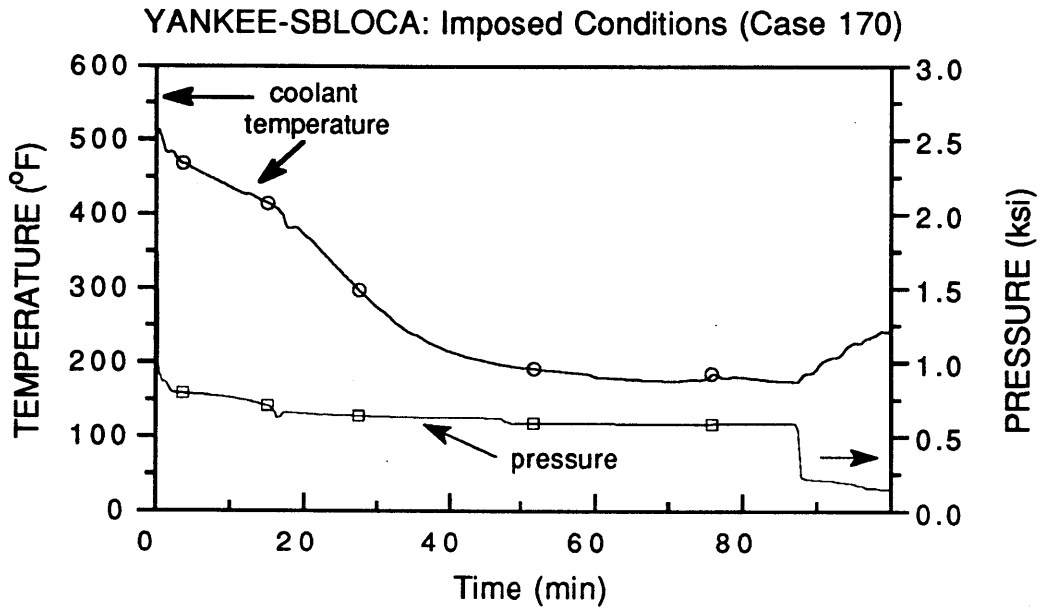
Fig.3.5 continued from the previous page



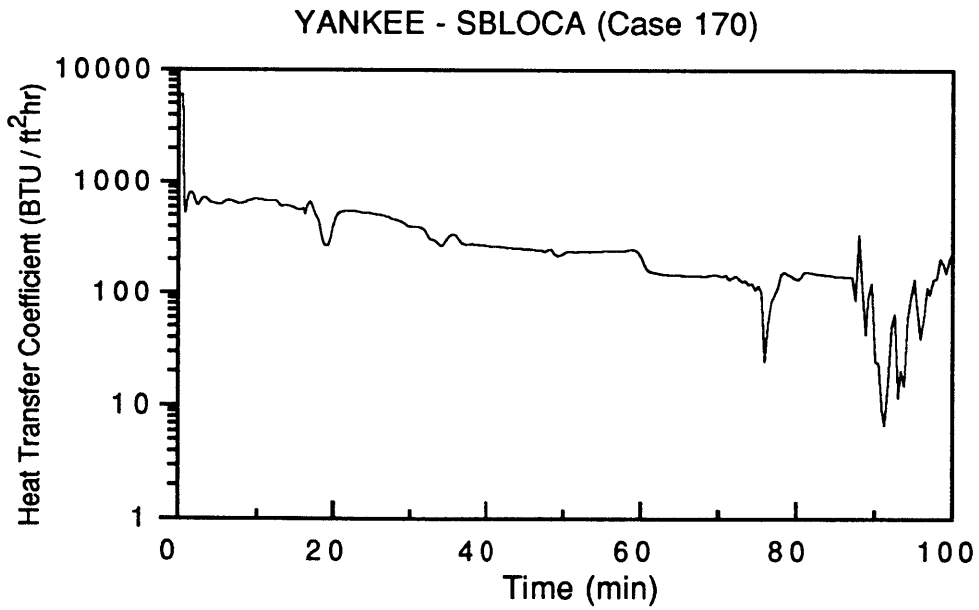
(e) Total stress distribution

Fig.3.5 continued from the previous page



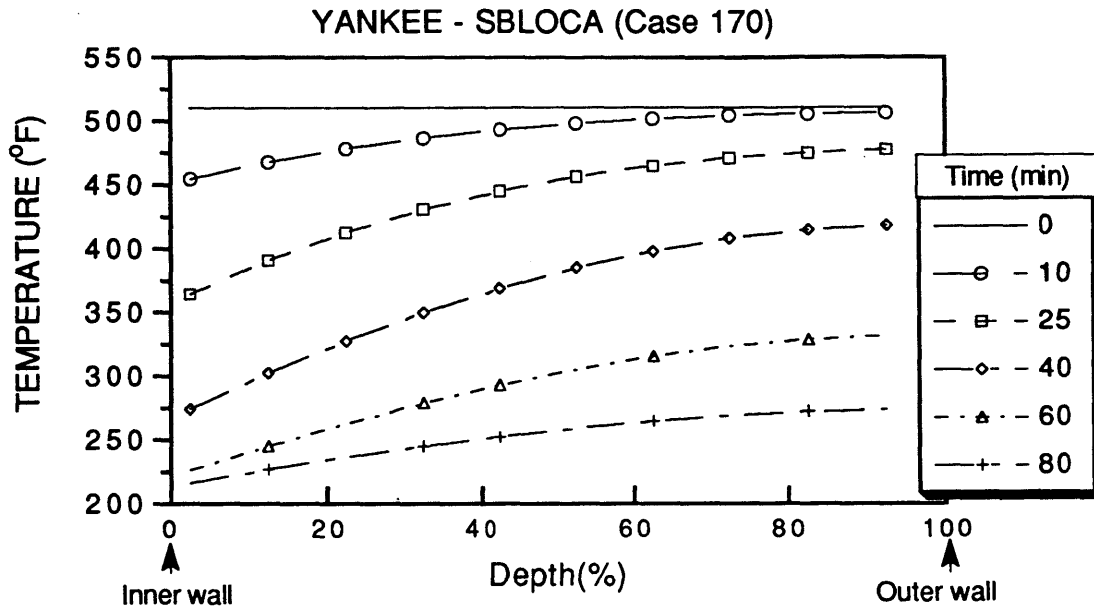


(a) Transient conditions

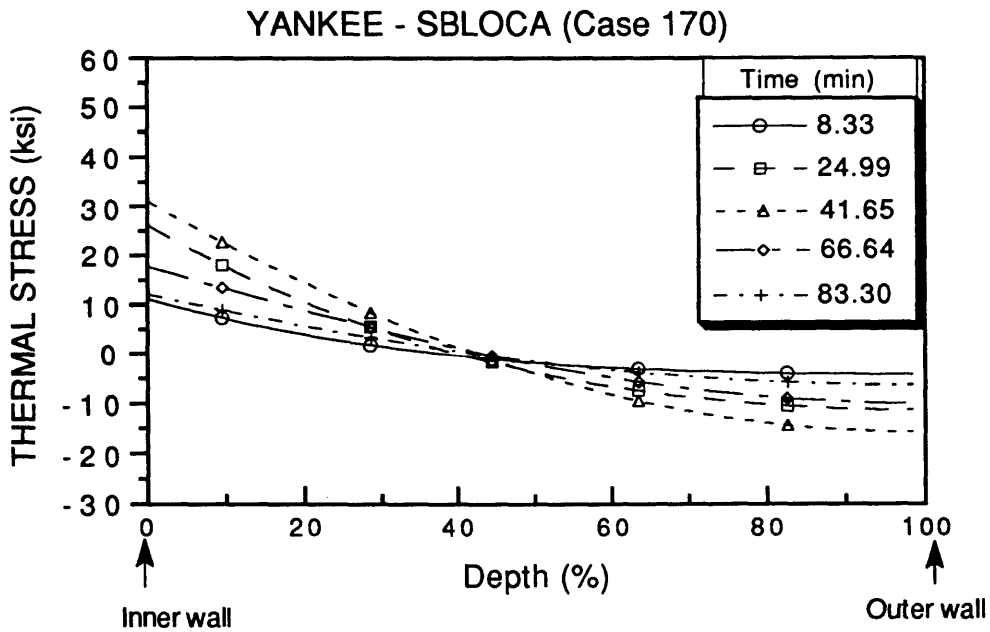


(b) Surface heat transfer coefficient

Fig. 3.6 Transient conditions and stress distributions in Yankee SBLOCA (Case 170)



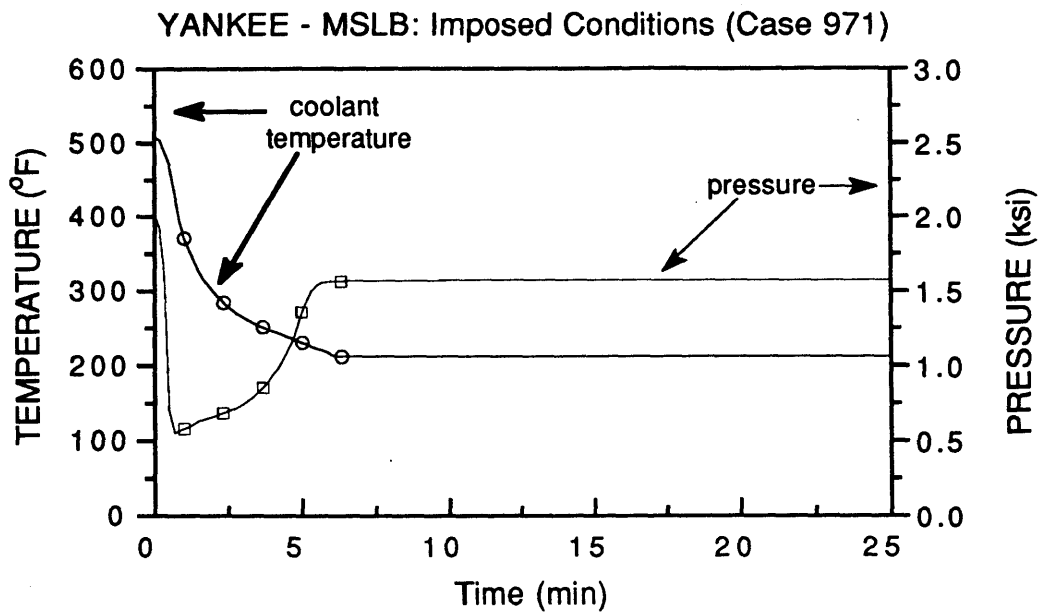
(c) Temperature distribution within the vessel wall



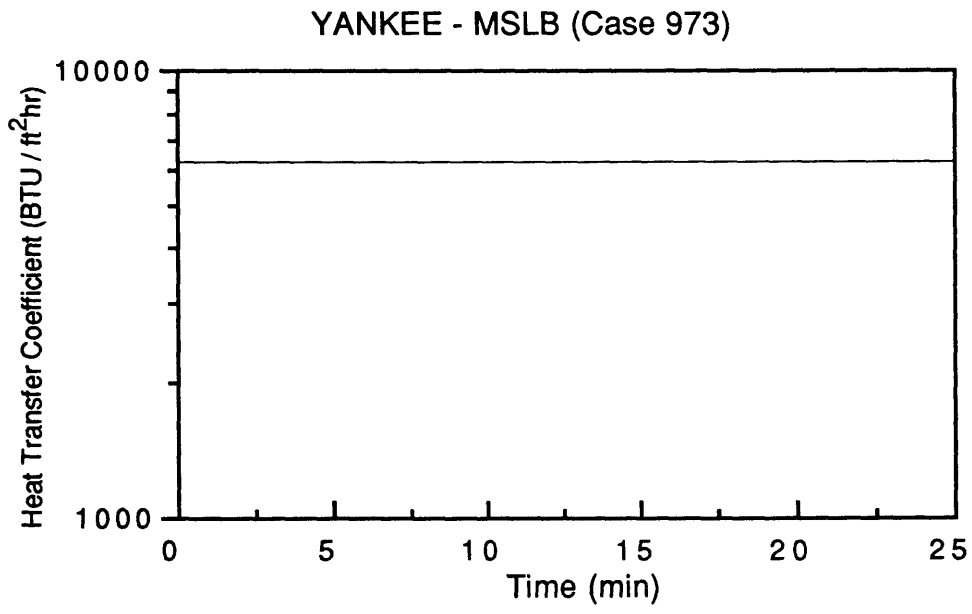
(d) Thermal stress distribution

Fig.3.6 continued from the previous page





(a) Transient conditions



(b) Surface heat transfer coefficient

Fig. 3.7 Transient conditions and stress distributions in Yankee MSLB (Case 971)

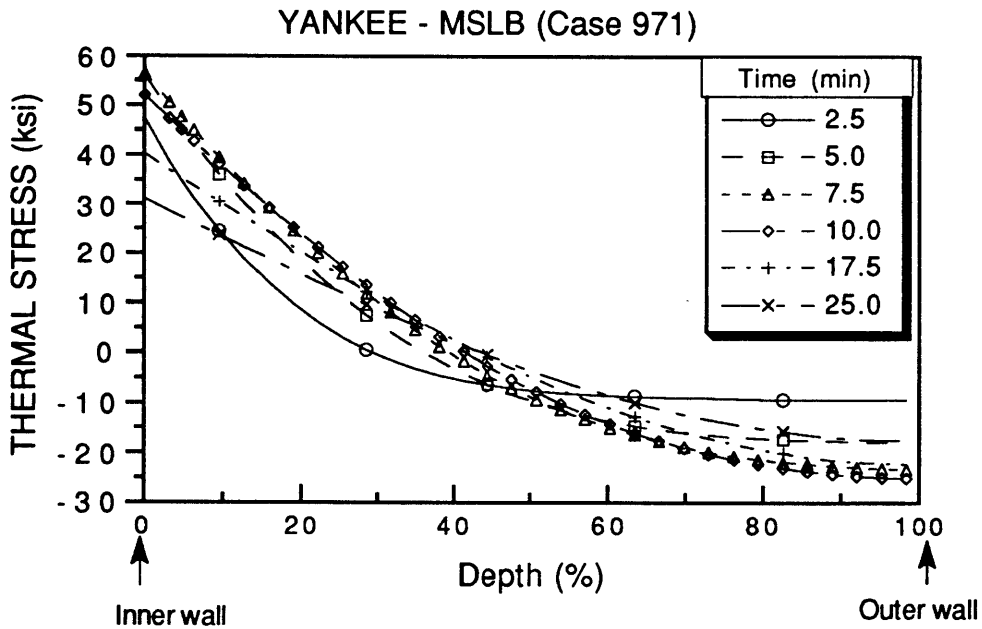
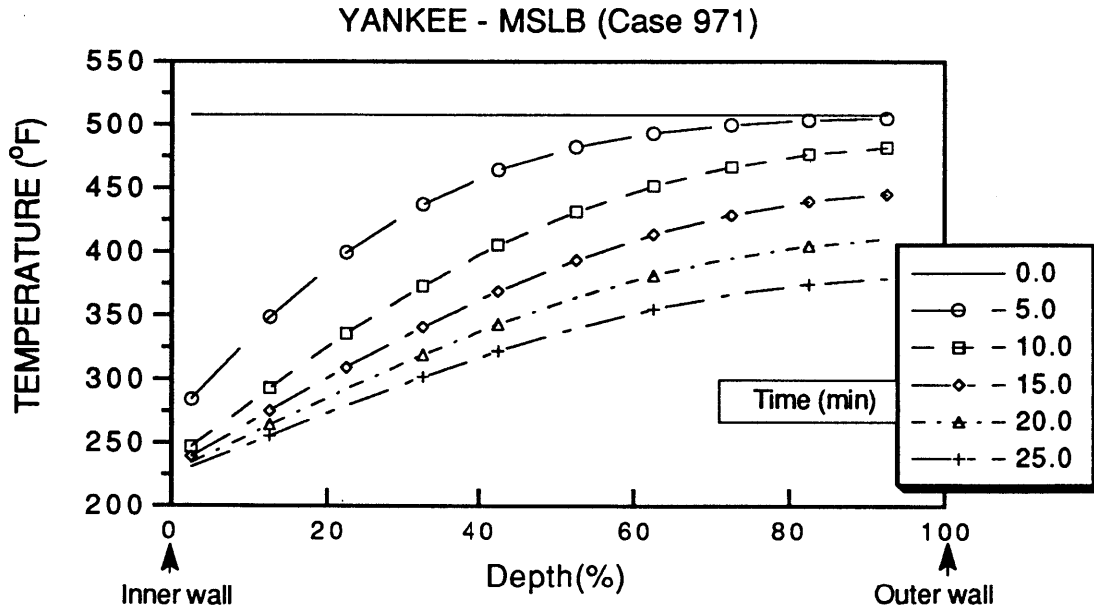
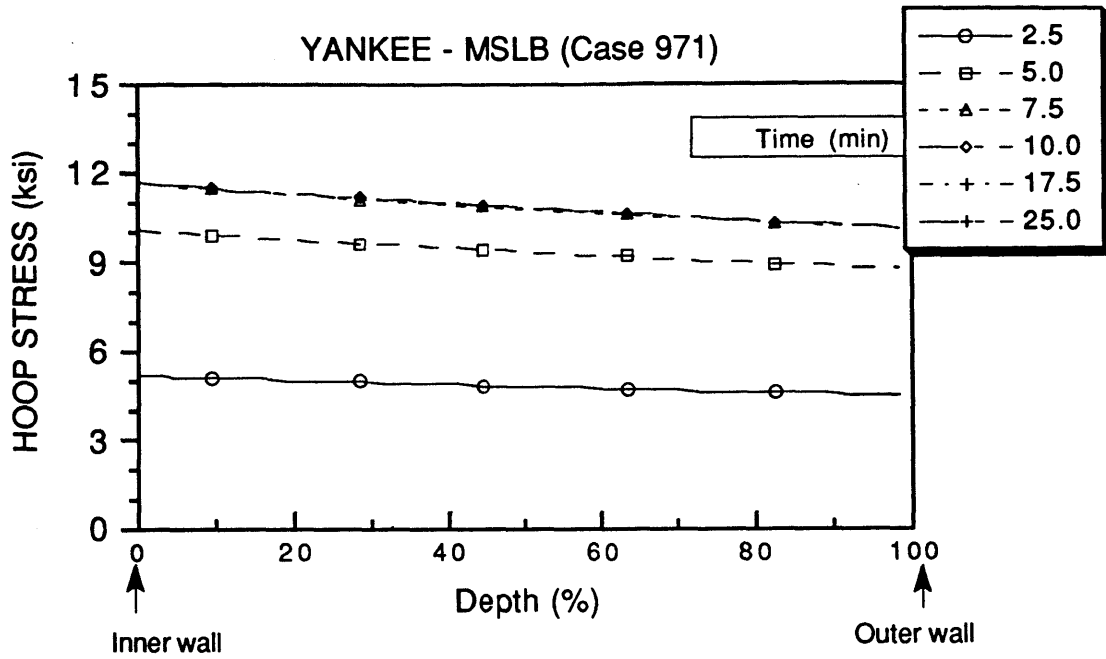
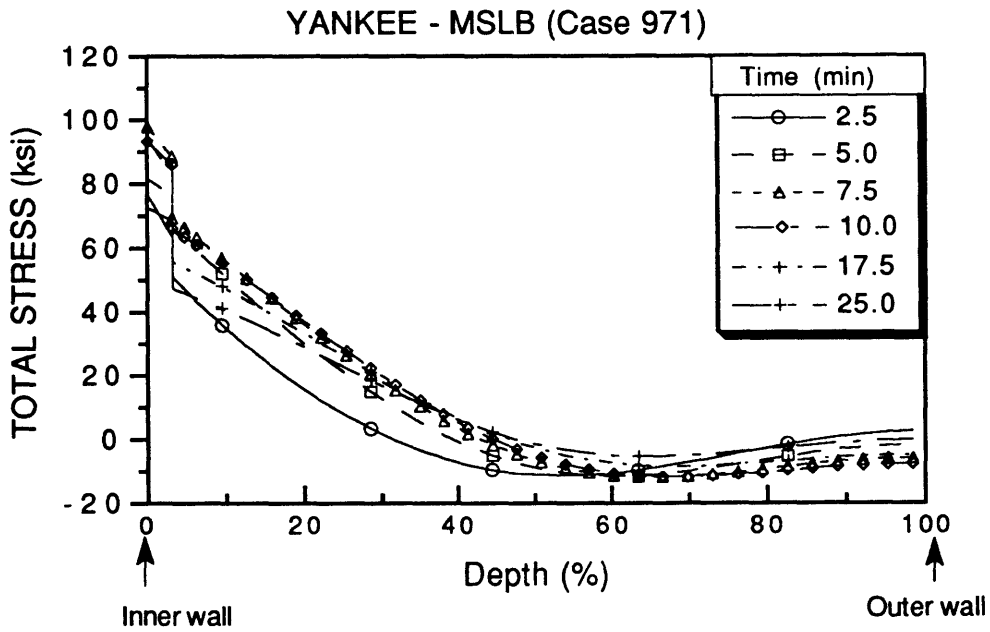


Fig.3.7 continued from the previous page

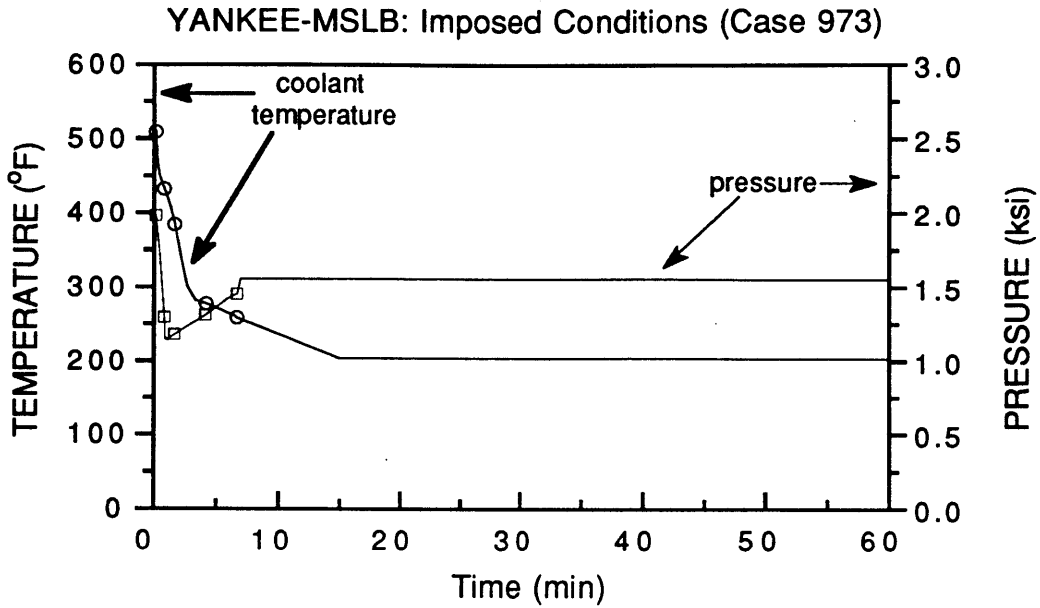


(e) Hoop stress distribution

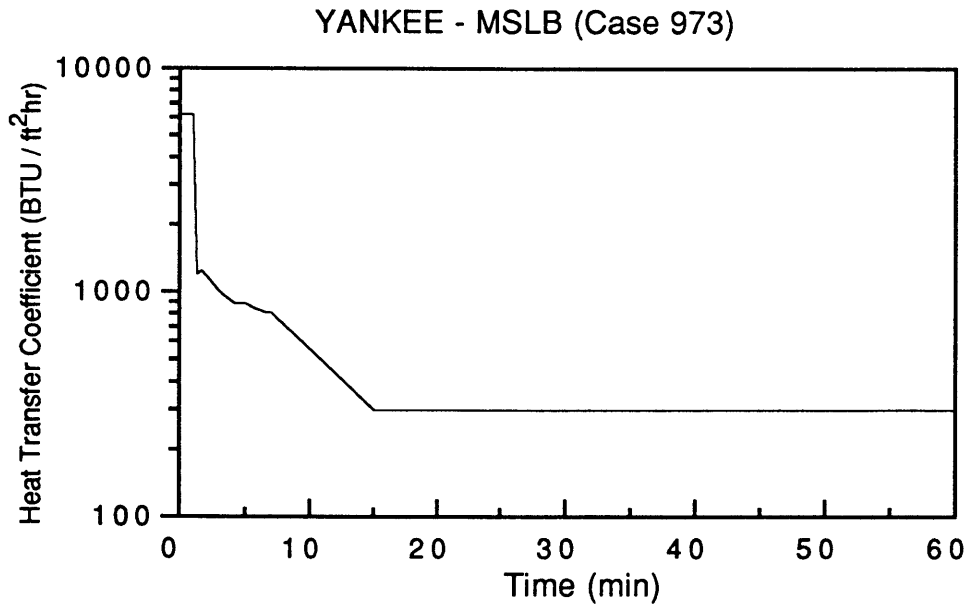


(f) Total stress distribution

Fig.3.7 continued from the previous page

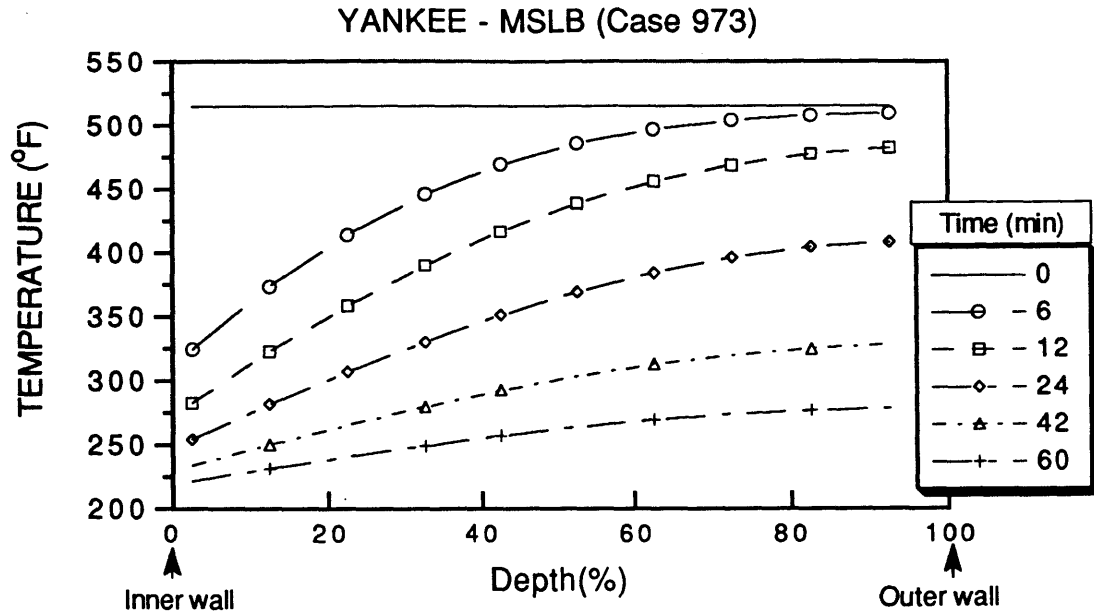


(a) Transient conditions

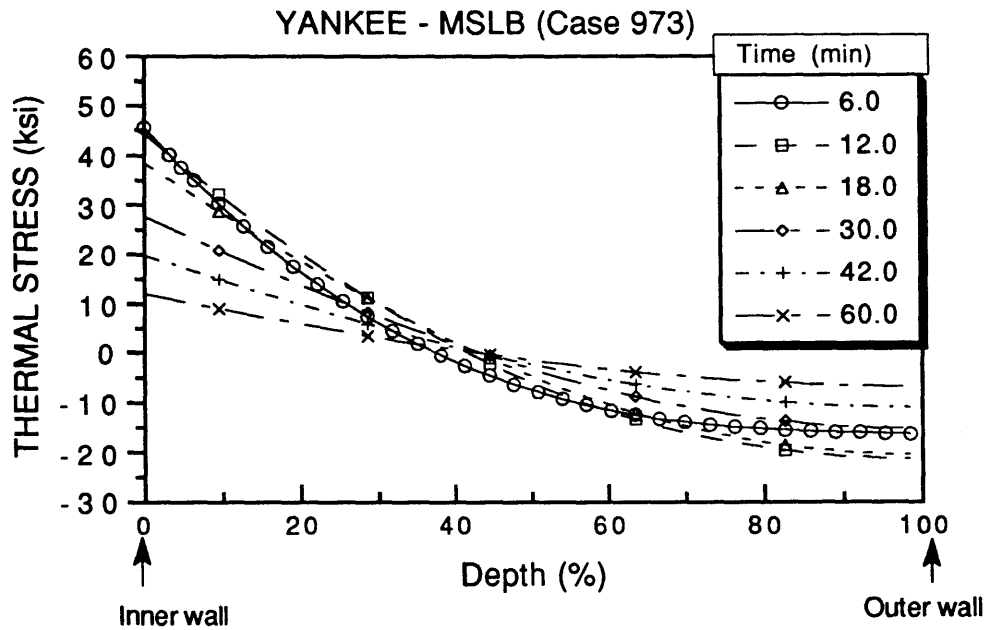


(b) Surface heat transfer coefficient

Fig. 3.8 Transient conditions and stress distributions in Yankee MSLB(Case 973)



(c) Temperature distribution within the vessel wall

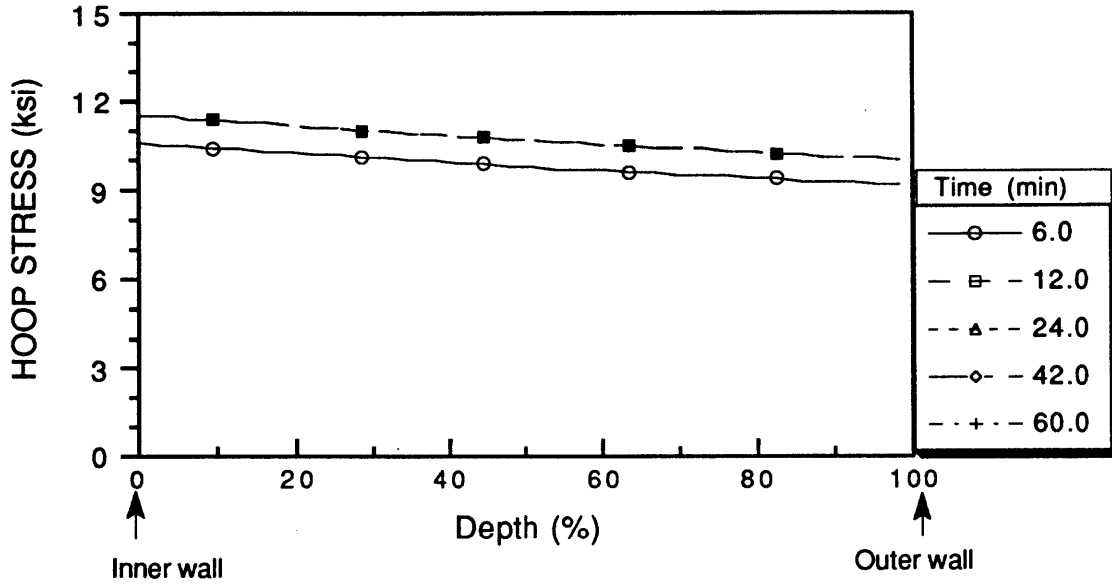


(d) Thermal stress distribution

Fig.3.8 continued from the previous page

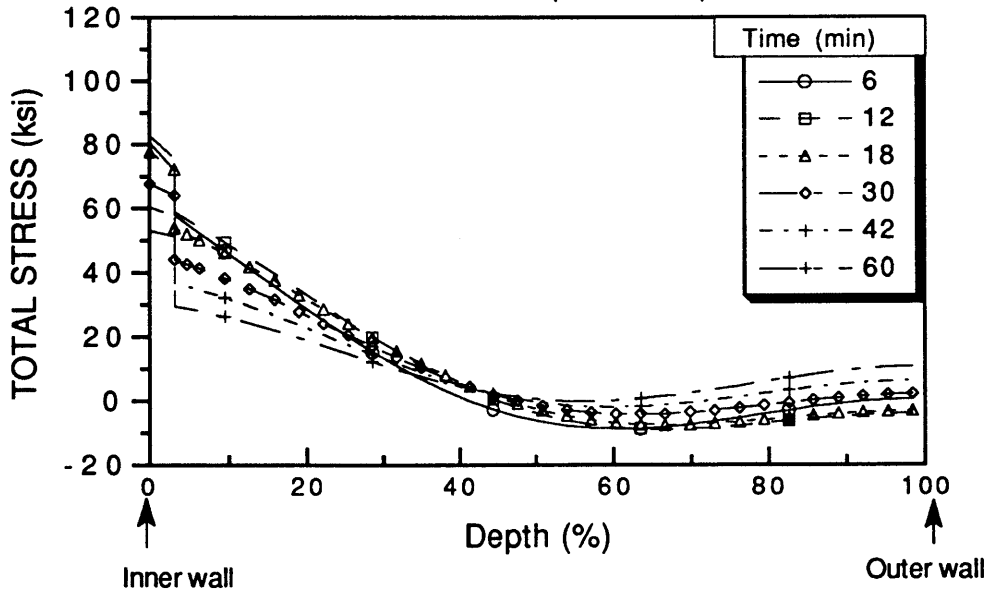


YANKEE - MSLB (Case 973)

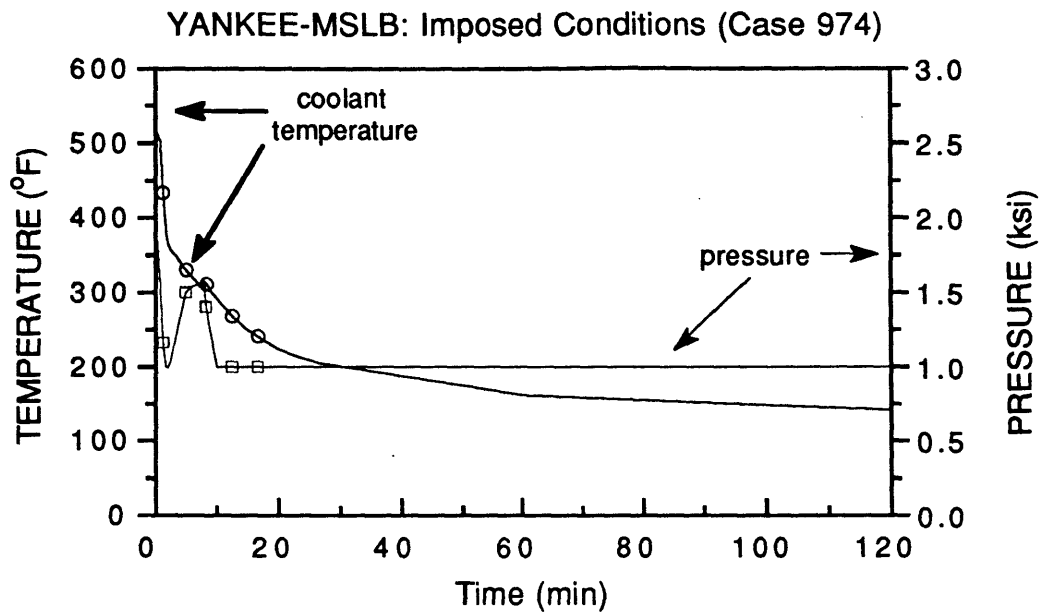


(e) Hoop stress distribution

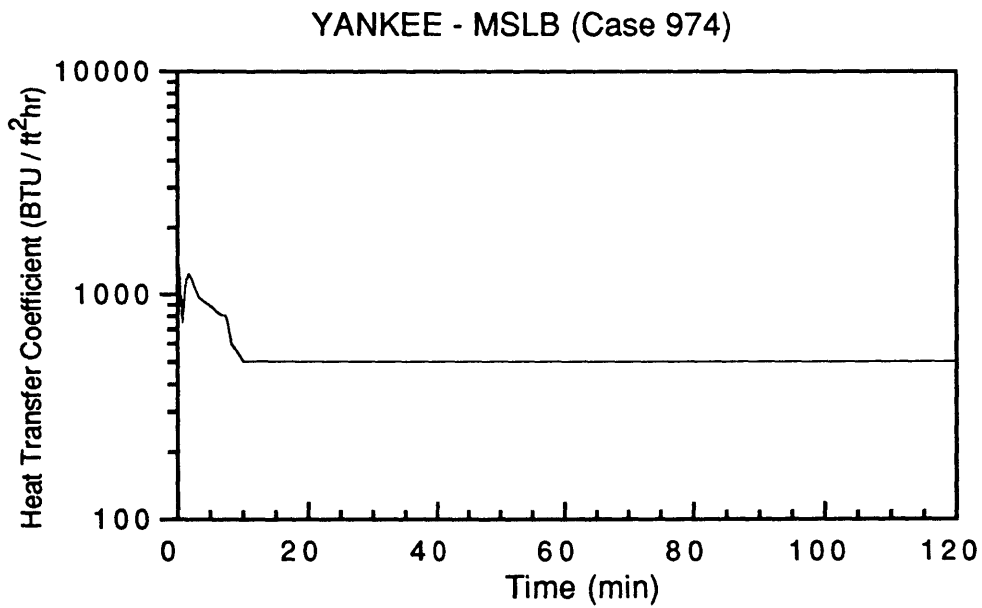
YANKEE - MSLB (Case 973)



(f) Total stress distribution



(a) Transient conditions



(b) Surface heat transfer coefficient

Fig. 3.9 Transient conditions and stress distributions in Yankee MSLB (Case 974)

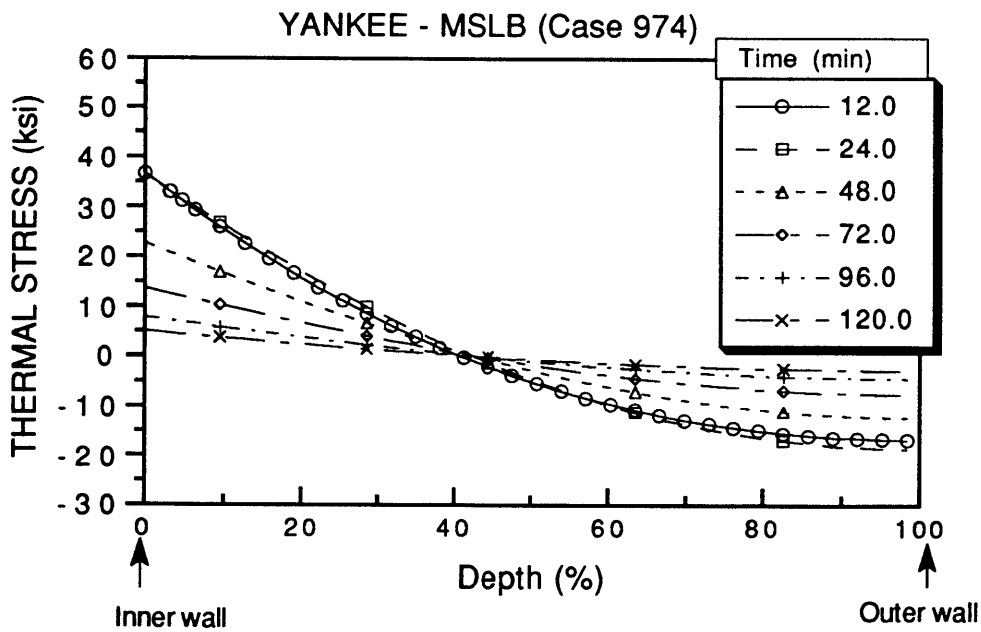
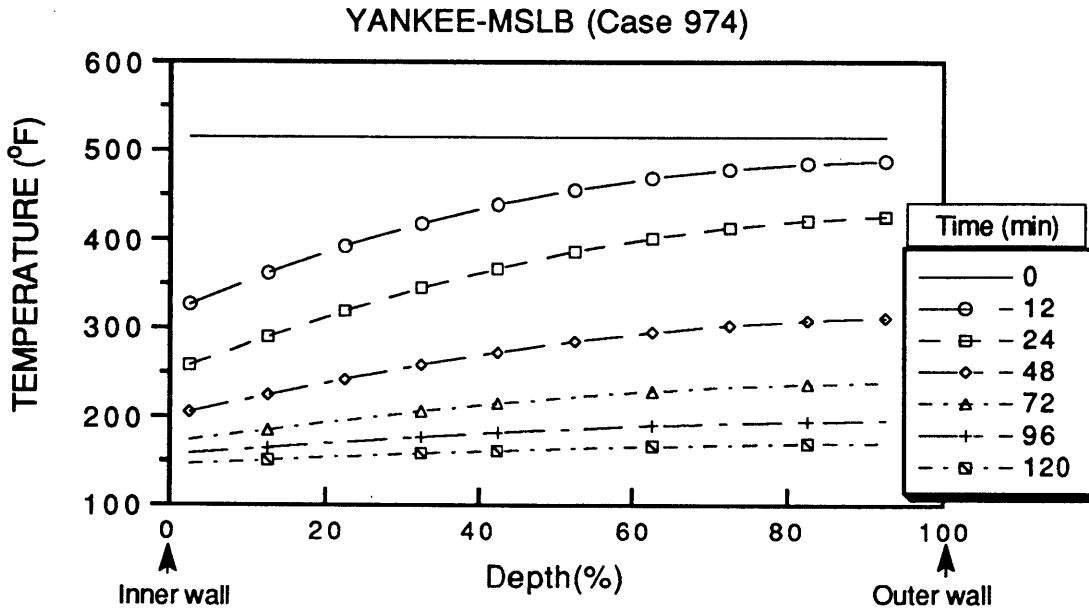


Fig.3.9 continued from the previous page



## **4. Discussion**

### **(1) Acceptability of the experimental method of the PTSE to PTS analyses**

In the PTSE tests, a flaw was implanted at the outer surface of the vessel and thermal shock was introduced by cooling the outer surface of the vessel with internal pressure. Therefore, tensile stress occurred at the outer surface of the vessel while the inner surface was subject to compressive stress. In actual PTS events of nuclear reactors, thermal shock occurs due to the cooling at the inside surface of the vessel with internal pressure. In this case, tensile stress occurs at the inner surface of the vessel.

Because flaws grow and propagate when they are subject to the tensile stress, the effect of thermal shock on the behavior of flaws are the same if the location of the flaws and cooling are the same. Therefore, the effect of thermal shock on the crack behavior observed in the PTSE is equivalent to the thermal shock effect on the behavior of flaws present at the inner surface of the reactor vessel which are major concern of PTS.

The hoop stress both in PTSE and Yankee Rowe cases is tensile because the vessels were internally pressurized. Also, the hoop stress does not significantly change for both PTSE and Yankee Rowe cases along the depth of the vessel wall as shown in the hoop stress figures in Section 3. Thus, the effect of internal pressure on the behavior of flaws is the same regardless of the location of flaws.

As a conclusion, the experimental method employed in the PTSE tests is acceptable for the investigation of the crack propagation which would occur in actual PTS events of a reactor vessel.

### **(2) Properties of Material**

One of the key factors determining the impact of PTS is the material toughness generally indicated by the reference nil-ductility temperature ( $RT_{NDT}$ ). Table 4.1 shows a comparison of  $RT_{NDT}$ 's among the PTSE and Yankee Rowe Reactor material summarized from Table 2.2, 2.3, 2.4, and 2.5. As noticed in Table 4.1, the  $RT_{NDT}$  of the Yankee Rowe is higher than the material tested in the PTSE. Thus, the Yankee Rowe Reactor Vessel is considered to be more vulnerable to pressurized thermal shock than the material tested in the PTSE. However, as mentioned in Section 2.3.5 and 2.3.6 of Ref.2, the exact  $RT_{NDT}$  of the PTSE-2 insert could not be defined because the insert did not achieve 68 J even on the upper shelf (the  $RT_{NDT}$  is defined as  $T_{68} - 33$  °K where  $T_{68}$  is the temperature at which the charpy V-notch impact energy is 68 J). The  $RT_{NDT}$  of PTSE-2 shown in Table 4.1 is the value obtained from the specimen presumed to have the same property of

the insert material. As observed by comparing the pretest material properties with the posttest material properties (see Table 2.3, 2.4, and Fig.2.8), it is believed that the insert material may have had lower toughness than the pretest material which has an  $RT_{NDT}$  of 210 °F. Ref.2 explains the change of material property before and after the tests in two reasons: plastic deformation occurring in the tests and the regional non-uniformity of the material from which the pretest specimen and insert were manufactured. If the non-uniformity of the material is the major reason of the discrepancy in material properties between the insert and pretest specimen, then, the  $RT_{NDT}$  of the PTSE-2 insert would be closer to the estimated  $RT_{NDT}$  of the Yankee Rowe Reactor Vessel. Further investigation on the  $RT_{NDT}$  of the PTSE-2 insert is recommended.

Table 4.1 A comparison of  $RT_{NDT}$  between PTSE and Yankee Rowe

	PTSE-1	PTSE-2 (pretest)	Yankee Rowe
$RT_{NDT}$ (°F)	196.3	210.2	275-350

### (3) Magnitude of stress

As noticed in Table 4.2, the magnitude of stress incurred by PTS is much smaller for the Yankee Rowe cases than for the PTSE cases. We may characterize the PTSE tests in contrast to the Yankee Rowe PTS as high toughness material with high stress versus low toughness material with low stress. It is hard to conclude whether or not flaws in the Yankee Rowe Reactor Vessel would propagate when PTS occurs based on the results of the PTSE alone because the toughness of the Yankee Rowe Reactor Vessel is not the same as the material used in the PTSE. In order to address the applicability of the PTSE results to the Yankee Rowe PTS consequence, further study is required on the relationship between toughness and applied stress regarding the crack behavior, i.e., whether and how much toughness and applied stress can be compensated with each other.

Table 4.2 Comparisons of the maximum stresses between PTSE and Yankee Rowe PTS

Case	Thermal Stress (ksi)	Hoop Stress (ksi)	Total stress (ksi)
PTSE-1A	100.1	12.2	102.1
PTSE-1B	106.8	24.3	116.6
PTSE-1C	102.6	38.5	124.2
PTSE-2A	111.4	25.6	128.0
PTSE-2B	98.2	26.2	98.9
SBLOCA (Case 170)	32.5	5.8	40.3
MSLB (Case 971)	58.1	11.7	69.4
MSLB (Case 973)	46.2	11.5	58.8
MSLB (Case 974)	38.6	7.4	47.8

Note: for the Yankee Rowe cases, the maximum stresses shown above are for the reactor vessel wall excluding the clad region.

(4) Effect of warm prestressing

Warm prestressing effect was recognized through the series of the PTSE, i.e., no crack propagation under decreasing  $K_I$  although  $K_I > K_{IC}$ . This observation is considered to help identify the transients important for PTS. For instance, main steam line break accident is considered to be a more serious event for PTS than small break LOCA, because pressure is more likely back up during the course of transients in main steam line break. Also, development of an operating procedure to limit unnecessary pressure surge is recommended to reduce the impact of PTS.

## **References**

1. Bryan, R. H. et al, " Pressurized-Thermal-Shock Test of 6-in.-Thick Pressure Vessels. PTSE-1: Investigation of Warm Prestressing and Upper-Shelf Arrest ", NUREG/CR-4106, Oak Ridge National Laboratory, April 1985.
2. Bryan, R. H. et al, " Pressurized-Thermal-Shock Test of 6-in.-Thick Pressure Vessels. PTSE-2: Investigation of Low Tearing Resistance and Warm Prestressing ", NUREG/CR-4888, Oak Ridge National Laboratory, December 1987.
3. Simoien, F. A. et al, " VISA-II - A Computer Code for Predicting the Probability of Reactor Pressure Vessel Failure ", NUREG/CR - 4486, Pacific Northwest Laboratory, March 1986.