13th International Conference on CANDU Fuel
Holiday-Inn Waterfront Hotel
Kingston, Ontario, Canada, 2016August 15-18

CANDU FUEL:
Evolution towards Optimal Performance

MODELLING OF CANDU PRESSURE TUBE DIAMETER EXPANSION

J.Y. JUNG[1]and W.J. Hartmann[2]
[1]Korea Atomic Energy Research Institute, Daejeon, Korea
(989-111, Daedeok-daero, Yuseong-gu, Daejeon, agahee@kaeri.re.kr)
[2]CANTECH, Ontario, Canada

ABSTRACT –Because expansion of the diameter of pressure tubes affects critical channel powers, an accurate prediction of the pressure tube diameter is very important in assessing the operational margin to fuel dryout. This study was focused on modelling of the pressure tube diameter expansion based on the operating conditions of the neutron flux and the coolant temperature in the pressure tube. It is well known that high temperature and neutron irradiation are the main parameters affecting pressure tube deformation. Accordingly, the pressure tube diameter expansion was modelled using the neutron flux and temperature distribution data of each channel and each bundle, as well as the available measured diameter data of pressure tubes.

Introduction

The pressure tube of a CANDU reactor is the most important part of the fuel channel because it passes through the calandria and contains the fuel bundles. However, measurements of the pressure-tube inside diameters at CANDU plants have shown that the diameters have been increasing over time. This phenomenon is due to the effects of irradiation by neutron flux, stress, and reactor operating temperatures over the plant life. This has been regarded as one of the principal aging mechanisms governing the heat transfer and hydraulic degradation of the heat transport system. The diametralexpansion of the pressure tube results in the reduction of fuel cooling due to the increased bypass flow, increases the possibility of fuel dryout, and thus limits the operating power of the reactor. Therefore, an accurate prediction of the pressure tube diameter is very important in assessing the operational margin to dryout.

Many studies have been carried out to understand the material behavior of the pressure tube under irradiation conditions [2-3], the effect of manufacturing variables on the pressure tube deformation [4] and to develop an appropriate model describing the pressure tube diametral creep [5-9]. Holt [1] summarized various aspects of pressure tube deformation modelling and described pressure tube creep as consisting of three parts (thermal creep, irradiation creep and irradiation growth) as follows:

$$\dot{\varepsilon} = \dot{\varepsilon}_{tc} + \dot{\varepsilon}_{ic} + \dot{\varepsilon}_{ig}$$

$\dot{\varepsilon}$: Strain rate for pressure tube creep

$\dot{\varepsilon}_{tc} = C_1(T,P)exp(-Q_1/T)$: Thermal Creep

$\dot{\varepsilon}_{ic} = C_2(T,P,x,\emptyset)exp(-Q_2/T)$: Irradiation Creep

$\dot{\varepsilon}_{ig} = C_3(T,P,x,\emptyset,t)exp(-Q_3/T)$: Irradiation Growth

T: temperature,P: coolant pressure,*x*: axial location, $\emptyset$: fast neutron flux,
t: irradiation time, Q_1, Q_2, Q_3: activation temperatures

Here, thermal creep changes the pressure tube diametral shape due to the effect of temperature and stress in the absence of a fast neutron flux. Irradiation creep changes the diametral shape due to irradiation, and irradiation growth is an additional change in diametral shape due to irradiation overtime. However, this modelling is too complex to determine every parameter and relevant constants appropriately.

This study was focused on the modelling of expansion of the pressure tube diameter based on the operating conditions of the neutron flux and the temperature. It is well known that high temperature and neutron irradiation are the main parameters affecting pressure tube deformation. Accordingly, the pressure tube diameter expansion was modelled using the neutron flux and temperaturedistribution of each channel and each bundle as well as the measured diametral data of pressure tubes. From the measured data, a creep strain rate was derived for each measured channel and normalized flux and temperature data for each corresponding channel was specifically derived. Although the basic concept of the current modelling approach is simple, prediction results of the pressure tube diameter show very good agreement with the measured data.

1. Analysis of Measured Data for Pressure Tube

Pressure tube diameters are inspected periodically to check their integrity during operation. Some pressure tubes have been inspected repeatedly and Figure 1 shows the inner diameter deformation trend of a specific pressure tube that has been inspected four times at 1500, 1930, 3210, and 5340 EFPD (Effective Full Power Day).

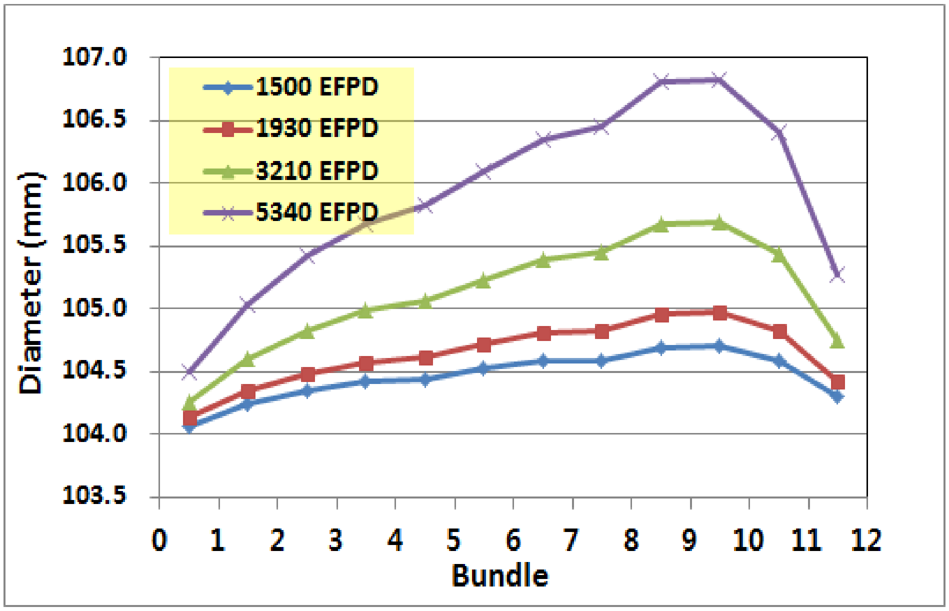

Figure 1 Measured Data for Pressure Tube Diameter

Diametral creep of the pressure tube depends on the neutron flux and temperature, and Figure 1 shows such a relation. Because the coolant temperature increases from the inlet to the outlet and the neutron flux is highestin the middle region of the pressure tube, the maximum diametral deformation occurs near the outlet region, especially near bundles 9 and 10, because of the combined effect of temperature and neutron flux.

Based on the measured data (Figure 1) for the pressure tube diameter, strain (%creep) was calculated using equation (1) and Table 1 shows the %creep results for each bundle position at each measured time.

$$\%\text{creep (strain)} = \frac{\Delta l}{l_0} \times 100 \quad (1)$$

Table 1 Pressure Tube Diametral Strain, %creep

EFPD	% creep, 1	% creep, 2	% creep, 3	% creep, 4
BD	1500	1930	3210	5340
1	0.193	0.257	0.378	0.601
2	0.359	0.459	0.700	1.113
3	0.460	0.592	0.925	1.489
4	0.525	0.679	1.076	1.742
5	0.548	0.715	1.151	1.881
6	0.627	0.817	1.312	2.136
7	0.688	0.902	1.459	2.385
8	0.693	0.916	1.515	2.488
9	0.789	1.044	1.733	2.833
10	0.797	1.055	1.748	2.839
11	0.690	0.912	1.501	2.438
12	0.409	0.536	0.845	1.355

Strain rate (%creep_rate) was derived based on the above %creep data using equation (2).Here, %creep_rate represents the variation of %creep per 1000 EFPD .

$$\%creep\_rate = \frac{\%creep}{kEFPD} = \frac{\%creep_{i+1} - \%creep_i}{EFPD_{i+1} - EFPD_i} \times \left(\frac{1000\,EFPD}{kEFPD}\right) \quad (2)$$

Table2Pressure Tube Diametral Strain Rate (%creep_rate)

BD	%creep_rate = %creep/kEFPD				
	measured, 1-2	measured, 2-3	measured, 3-4	measured_ave	measured, 1-4
1	0.150	0.095	0.104	0.116	0.106
2	0.234	0.188	0.194	0.205	0.196
3	0.306	0.260	0.265	0.277	0.268
4	0.357	0.310	0.313	0.327	0.317
5	0.387	0.341	0.342	0.357	0.347
6	0.442	0.387	0.387	0.405	0.393
7	0.498	0.435	0.435	0.456	0.442
8	0.520	0.468	0.456	0.482	0.467
9	0.593	0.539	0.516	0.549	0.532

10	0.599	0.541	0.512	0.551	0.532
11	0.518	0.460	0.440	0.473	0.455
12	0.294	0.242	0.239	0.258	0.246

Table 2 summarizes %creep_rate results for each time period. The fifth column of Table 2 is the average %creep_rate calculated by averaging columns two to four. The average values of %creep_rateare higher than the measured %creep_rate between 1500 and 5340 EFPD summarized in the sixth column. This is clearly demonstrated in Figure 2. As shown in this figure, %creep_ratehas decreased according to the operation time. For example, the blue solid curve ("measured, 1-2" in Figure 2) is the %creep_rate between 1500 EFPD and 1930 EPFD and the green solid curve ("measured, 3-4" in Figure 2)is the %creep_rate between 3210 and 5340 EFPD. In this study, the average %creep_rate, represented by the red dotted curve (the average of thethree%creep_rate from each different time period), was used as the representative measured %creep_rate for the whole operation time.

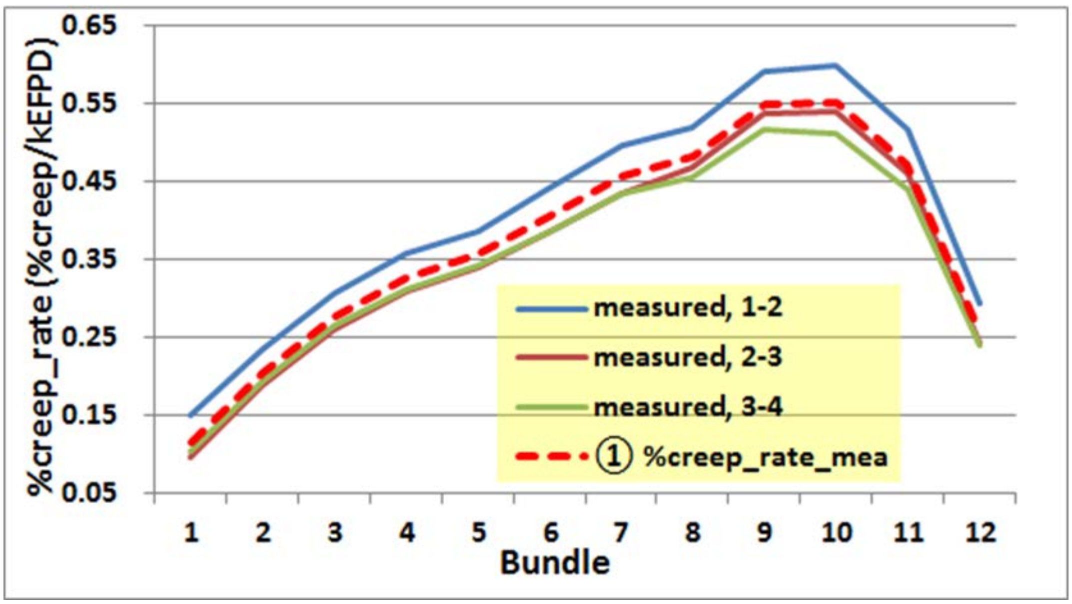

Figure 2 Measured %creep_rate for Each Time Period

2. Normalization of Operating Conditions

Normalization of the operating conditions was done for the neutron flux, bundle power, temperature and pressure at each bundle location. Neutron flux and bundle power were normalized in two ways.The first is normalization by the maximum channel flux and power of the 380 channels and the other is normalization done by the maximum bundle flux and power of all 4560 bundles in the core. Figure 3 shows normalized values of the operating conditions. Normalized flux and bundle power by maximum channel values were changed by multiplying by 10 (N_BD Power(CH) and N_Fast Flux(CH) in Figure 3) because of their small values. N_BD Power(BD) and N_Fast Flux(BD) are the normalized results of bundle power and neutron flux by the maximum bundle flux and power. It can be seen that the normalized results of neutron flux and bundle power are mostly similar, so one of them could be used in the modelling of pressure tube diameter prediction. Temperature and pressure at each bundle location were normalized by their respective maximum value and the results are also shown in Figure 3. The variation of the temperature along the axial locations of the channel was greater than was the variation of pressure. These normalized results of the operating conditions were used in the modelling of pressure tube diameter prediction.

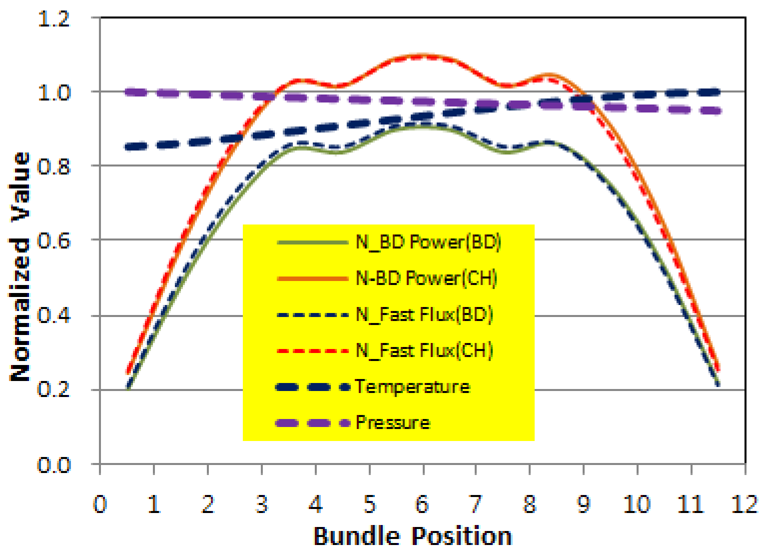

Figure 3 Normalized Operating Conditions

3. Modeling of PT Diameter Evaluation

As described in the Introduction, because the existing methodology for evaluating the diametral deformation of the pressure tube is very complex, the pressure tube diameter has been modeled using only the neutron flux (or bundle power) and temperature via equation (3).

$$\%creep\_rate_{model} = \%creep\_rate_{flux} + \%creep\_rate_{temp} \quad (3)$$

As shown in Figure 3, the normalized results for the neutron flux and bundle power are almost identical. The basic concept of this approach to model the pressure tube diameter, was initiated from the general deformation shape of the pressure tube diameter. This could be expressed by combining the distribution of the neutron flux and temperature along the pressure tube axial location as shown in Figure 4 [10].

Table 3 summarizes the results from each modeling procedure for the pressure tube diameter evaluation. The second column of Table 3 is the %creep_rate calculated from the measured data explained in Section 1. Values of the second column ($\%creep\_rate_{BDP}$) are the scaled results from the normalized values of the bundle power by the maximum channel power described in the previous section. They are depicted as curve ① and ② in Figure 5. Differences between the $\%creep\_rate_{mea}$ (①) and $\%creep\_rate_{BDP}$ (②) are summarized in the fourth column of Table 3, and curve ③ in Figure 5. Here, curve ③ increases along the axial position and it is very similar in behavior to the temperature distribution of the pressure tube. Thus, the effect of temperature on the pressure tube diametral creep, (i.e. $\%creep\_rate_{temp}$ (④)) was derived based on the above differences and is shown in the fifth column of Table 3 and curve ④in Figure 5. Then, the final results of $\%creep\_rate_{model}$ can be obtained by adding the $\%creep\_rate_{BDP}$ (②) and $\%creep\_rate_{temp}$ (④). They are summarized in the sixth column of Table 3 and curve ⑤ in Figure 5. From curve ① ($\%creep\_rate_{mea}$) and curve ⑤ ($\%creep\_rate_{model}$), the modelled %creep_rate based on the bundle power and temperature are in reasonable agreement with the measured %creep_rate, especially near the outlet region at which the maximum diametral deformation occurs. Curve ⑥, which is the difference between the measured %creep_rate and modelled %creep_rate, shows this relation clearly.

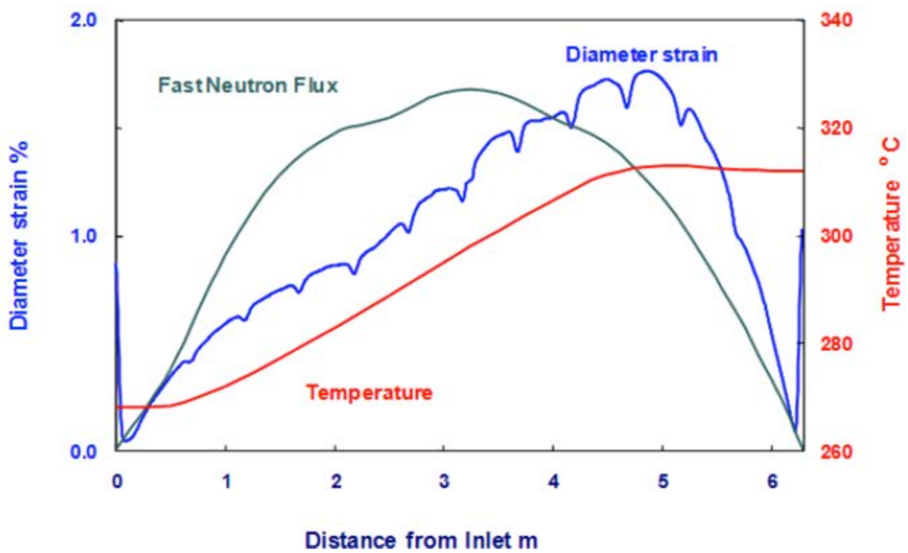

Figure 4 Pressure Tube Diametral Deformation and Operating Conditions [10]

Table 3 Modeling Procedure for the Pressure Tube Diameter Evaluation

BD	①	②	③=①-②	④	⑤=②+④	⑥=①-⑤
	$\%creep\_rate_{mea}$ (%creep/kEFPD)	$\%creep\_rate_{BDP}$	Difference	$\%creep\_rate_{temp}$	$\%creep\_rate_{model}$ (BDP+temp)	Difference
1	0.116	0.0701	0.0462	0.0201	0.0902	0.0261
2	0.205	0.1679	0.0374	0.0502	0.2181	-0.0128
3	0.277	0.2443	0.0328	0.0803	0.3246	-0.0475
4	0.327	0.2922	0.0346	0.1104	0.4026	-0.0758
5	0.357	0.2905	0.0663	0.1405	0.4310	-0.0742
6	0.405	0.3116	0.0937	0.1706	0.4823	-0.0770

7	0.456	0.3115	0.1444	0.2008	0.5123	-0.0564
8	0.482	0.2905	0.1910	0.2309	0.5214	-0.0398
9	0.549	0.2983	0.2509	0.2610	0.5593	-0.0101
10	0.551	0.2597	0.2913	0.2911	0.5508	0.0002
11	0.473	0.1831	0.2895	0.2911	0.4742	-0.0016
12	0.258	0.0760	0.1823	0.2008	0.2768	-0.0184

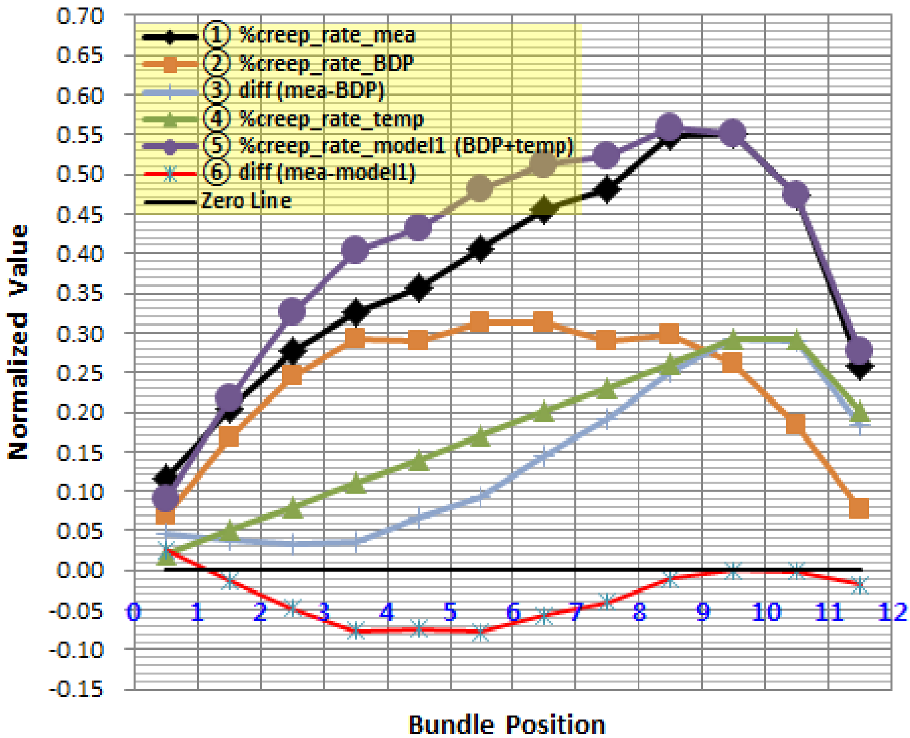

Figure 5 ResultsforPressure Tube Diameter Modeling

4. Conclusions

In this study, a modelling methodology was established for pressure tube diametral deformation based on operating conditions as well as measured data. Neutron flux and temperature distributions were used as basic parameters to represent the diametral deformation because they are the main parameters that affect pressure tube deformation. From the measured data, a creep strain rate was derived for each measured channel and normalized flux and temperature data for each corresponding channel was derived specifically. Although the basic concept of the current model is simple, prediction results for the pressure tube diameter from it show very good agreement with the measured data. Because this study has laid out the basic concept and modeling procedure for how to model the pressure tube diametral deformation, more research for more channels should be carried out to verify the established methodology.

5. References

[1] R.A. Holt, "In-Reactor Deformation of Cold-worked Zr-2.5Nb Pressure Tubes", Journal of Nuclear Materials, Vol. 372, 2008, pp 182-214.
[2] P.A. Ross and C.E.L. Hunt, "The In-Reactor Creep of Cold-Worked Zircaloy-2 and Zirconium-2.5 wt% Nobium Pressure Tubes", Journal of Nuclear Materials, Vol. 26, 1968, pp. 2 -17.
[3] B.Watkins and D.S. Wood, "The Significance of Irradiational-Induced Creep on Reactor Performance of a Zircaloy-2 Pressure Tube", ASTM-STP, Vol. 458, 1969. pp. 226-240
[4] G.A. Bickel and M. Griffiths, "Manufacturing Variablility, Microstructure and Deformation of Zr-2.5Nb Pressure Tubes", Journal of ASTM International, Vol. 4, No. 10, 2007.
[5] Y.Yung Liu and L. Bernet, "A Regression Approach for Zircaloy-2 In-Reactor Creep Constitutive Equations", Energy Laboratory Report No MIT-EL 77-012, Massachusetts Institute of Technology, Cambridge, Massachusetts, 1977.
[6] N. Christodoulou, A.R. Causey, R.A. Holt, R.A. Tome, C.N. Badie, N. Klassen, R.J. Sauve and C.H. Woo, "Modeling In-Reactor Deformation of Zr-2.5Nb Pressure Tubes in CANDU Power Reactors", Zirconium in the Nuclear Industry: Eleventh International Symposium, ASTM STP 1295, American Society for Testing and Materials, 1996, pp. 518-537.
[7] J.Y. Lee and M.G. Na, "Prediction of Diametral Creep for Pressure Tubes of a Pressurized Heavy Water Reactor Using Data Based Modeling", Nuclear Engineering and Technology, Vol. 44, No. 4, 2012, pp.355-362.
[8] A. Sarkar, S.K. Sinha, J.K. Chakravartty and R.K. Sinha, "ArtificialNeural Network Modelling of In-Reactor Diametral Creep of Zr-2.5%NbPressure Tubes of IndianPHWRs", Annals of Nuclear Energy, Vol. 69, 2014, pp.246-251.
[9] J.Y. Jung, “Database and Prediction Model for CANDU Pressure Tube Diameter”, Proceedings of the 19th Pacific Basin Nuclear Conference, Vancouver, British Columbia, Canada, 2014 August 24-28.
[10] G.A. Bickel and M. Griffiths, “Manufacturing and Microstrucre Effects on the Irradiation Deformation of Zr-2.5Nb Pressure Tubing”, IAEA Workshop on the Prediction of Axial and Radial Creep in HWR Pressure Tubes, Vienna, Austria, 2011November16-18.

Acknoledgements

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (Ministry of Science, ICT, and Future Planning).
(No. NRF-2012M2A8A4025960).