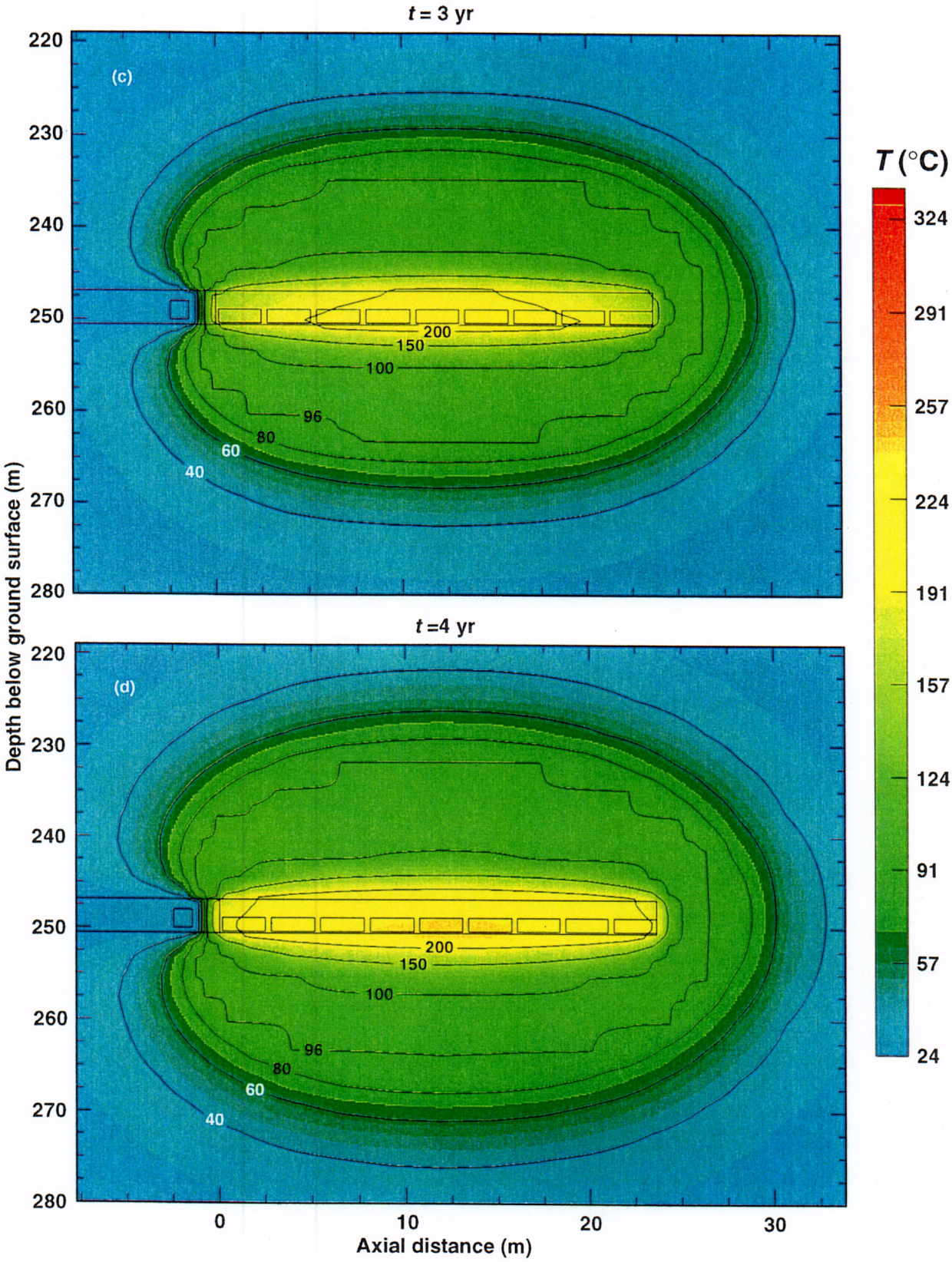

Figure 5.19. Temperature *T* distribution at (c) 3 and (d) 4 yr in the vertical axial midplane of the heater drift for 6.2-mm/yr percolation flux. The initial drift/wing-heater power is 80/100% of full capacity. For 4–5 yr, the power is linearly ramped down to 0/0%.

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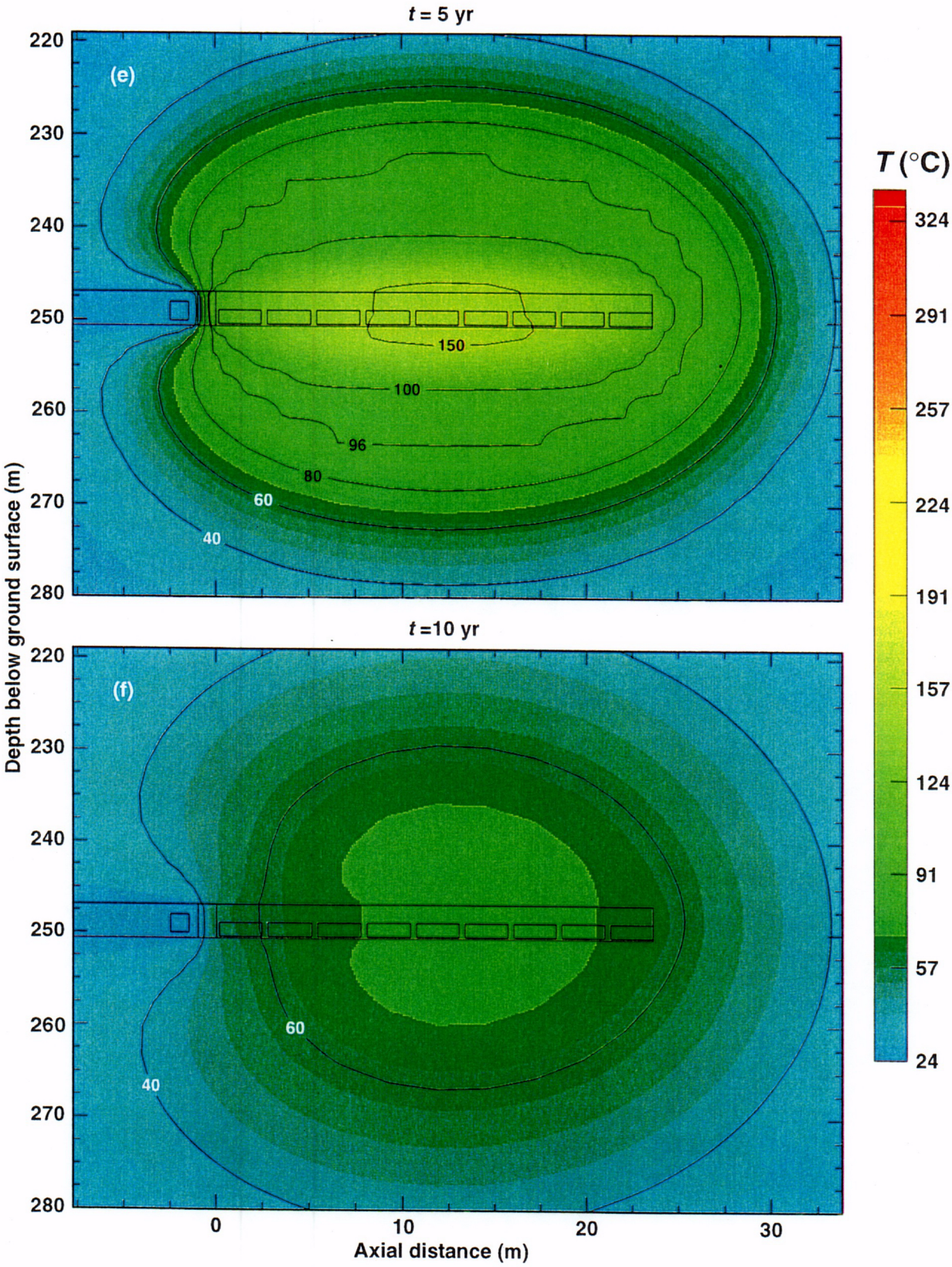

Figure 5.19. Temperature *T* distribution at (e) 5 and (f) 10 yr in the vertical axial midplane of the heater drift for 6.2-mm/yr percolation flux. The initial drift/wing-heater power is 80/100% of full capacity. For 4–5 yr, the power is linearly ramped down to 0/0%.

TB-6/5/97-T54zy.5-10y

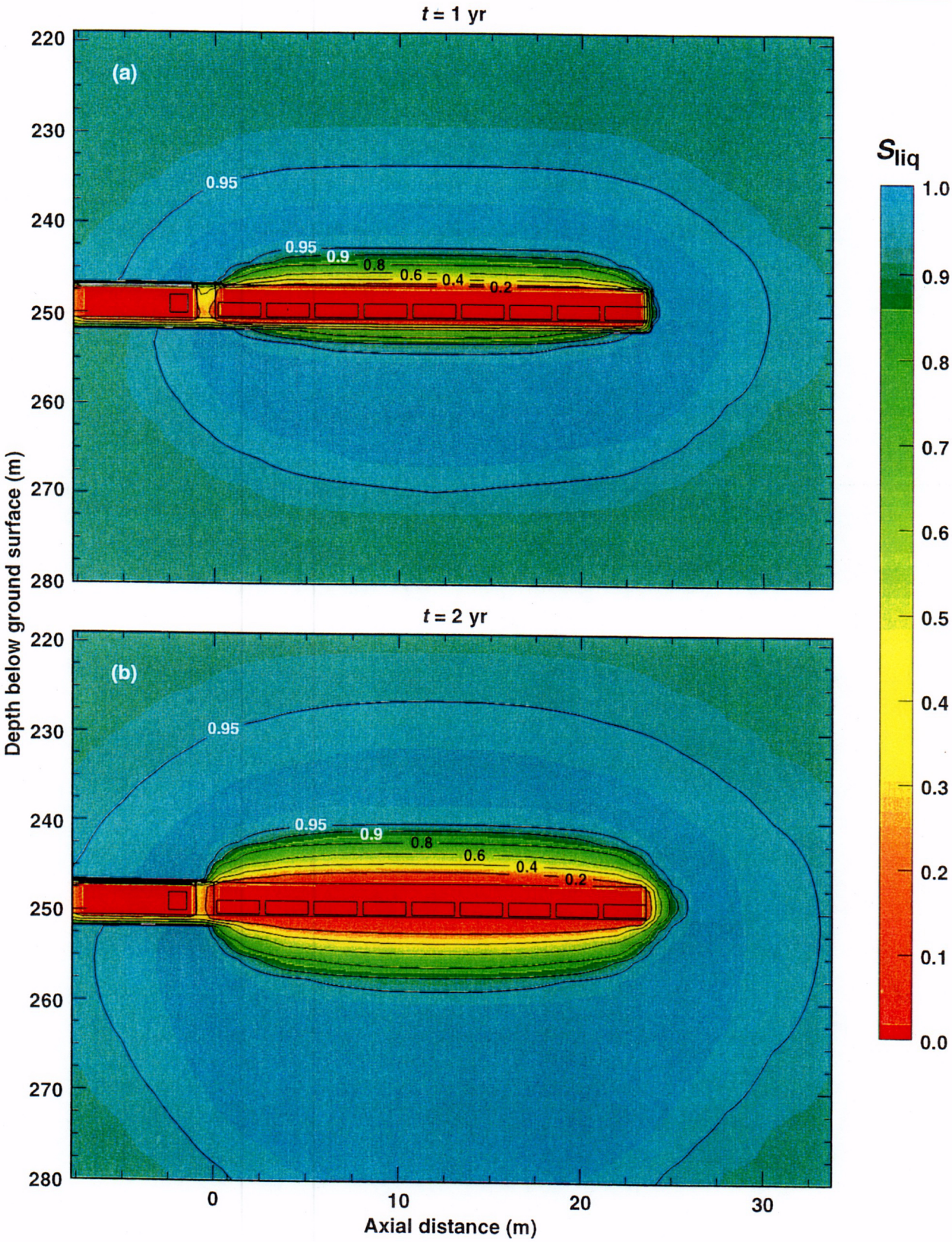

Figure 5.20. Liquid-phase saturation S_{liq} distribution at (a) 1 and (b) 2 yr in the vertical axial midplane of the heater drift for 6.2-mm/yr percolation flux. The initial drift/wing-heater power is 80/100% of full capacity. For 4–5 yr, the power is linearly ramped down to 0/0%.

TB-6/5/97-S54zy.1-2y

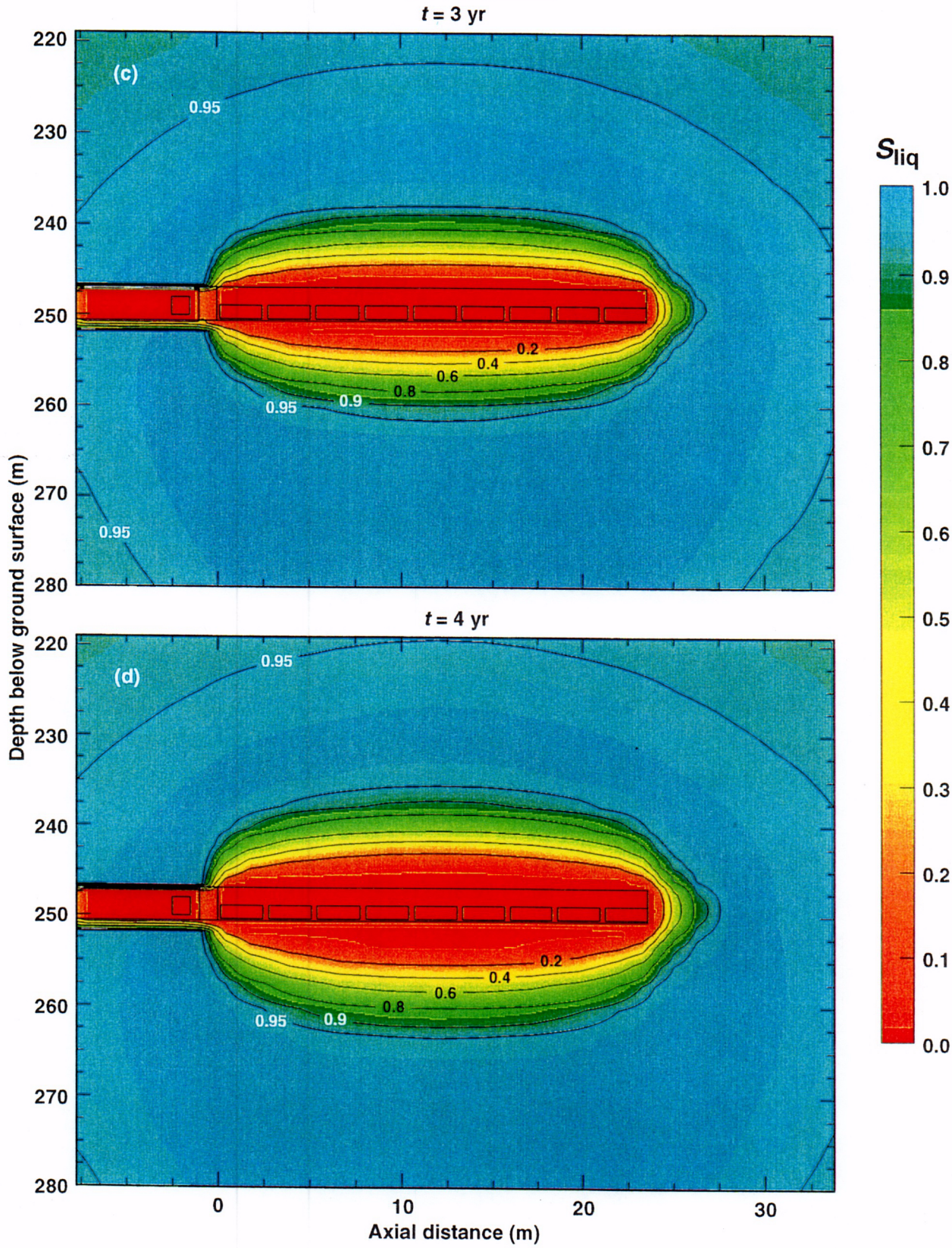

Figure 5.20. Liquid-phase saturation S_{liq} distribution at (c) 3 and (d) 4 yr in the vertical axial midplane of the heater drift for 6.2-mm/yr percolation flux. The initial drift/wing-heater power is 80/100% of full capacity. For 4–5 yr, the power is linearly ramped down to 0/0%. TB-6/5/97-S54zy.3-4y

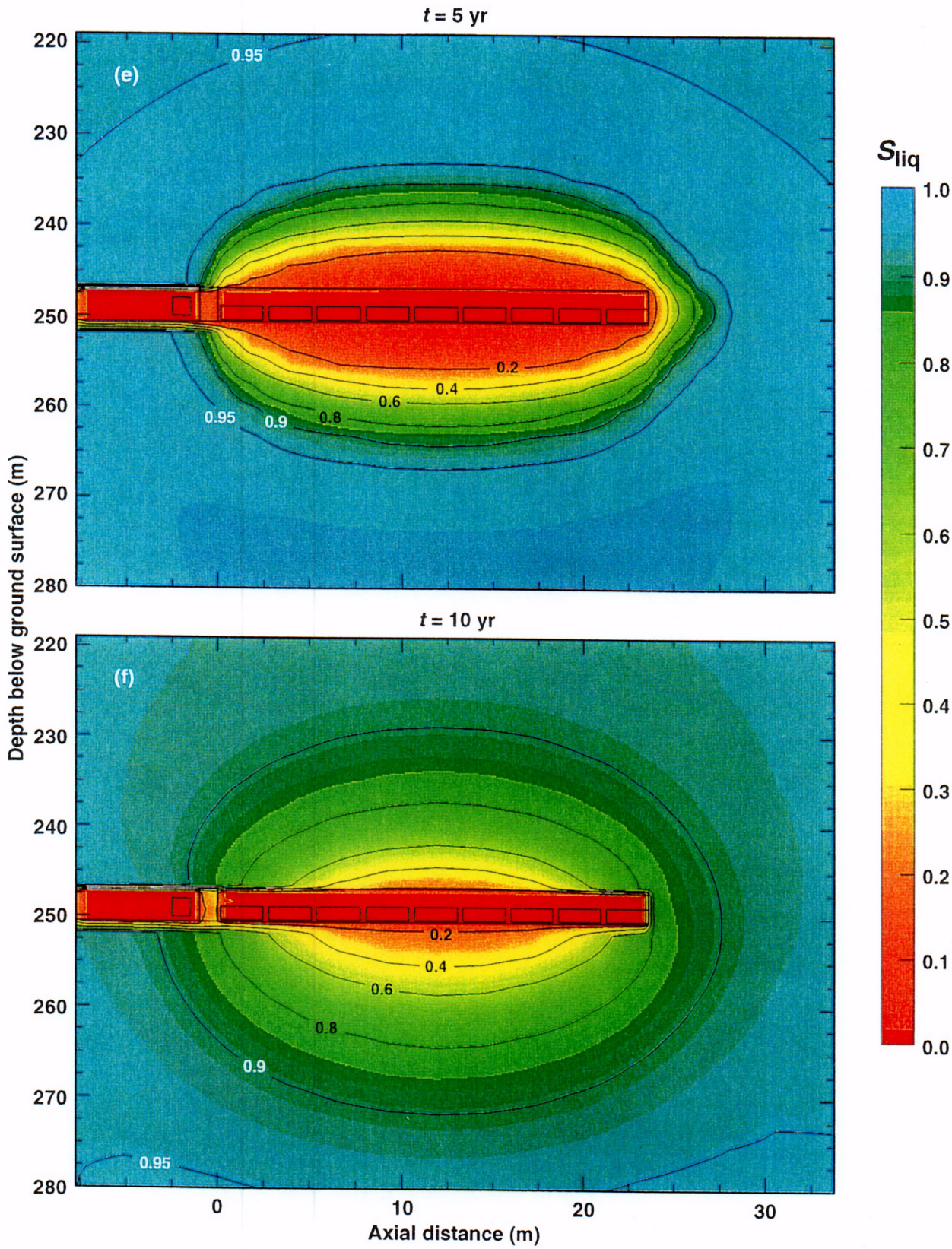

Figure 5.20. Liquid-phase saturation S_{liq} distribution at (e) 5 and (f) 10 yr in the vertical axial midplane of the heater drift for 6.2-mm/yr percolation flux. The initial drift/wing-heater power is 80/100% of full capacity. For 4–5 yr, the power is linearly ramped down to 0/0%. TB-6/5/97-S54zy.5-10y

Chapter 6

Analysis of Heating Rates and Schedules

6. Analysis of Heating Rates and Schedules

In this chapter, T-H model calculations are presented to help guide refinements to the design and operational plans of the DST test. Calculations were made for two of the three percolation-flux q_{perc} cases considered in Chapter 5 (q_{perc} = 0.36 mm/yr and q_{perc} = 3.6 mm/yr). Various heating rates and heating schedules are considered to provide input to help determine how the DST should be operated for an optimal balance among the following:

- Generating T-H conditions relevant to repository thermal loading conditions
- Elucidating a clear understanding of the influence of coupled T-H-M-C processes on dryout and rewetting
- Providing timely information for making repository-system design decisions and for validating process-level models supporting the total systems performance assessment for the license application (TSPA-LA)

For most of the cases conducted in this study, the initial heating rate is 80% full capacity for the in-drift heaters and 100% full capacity for the wing-heater arrays. As described in Chapter 5, this "80/100%" heating configuration causes tabular boiling and dryout zones (i.e., the upper and lower boiling and dryout fronts are nearly horizontal), which tends to minimize the tendency for condensate-shedding around the lateral edges of the heated area. Depending on the percolation flux and hydrological properties of the fracture and matrix continua, the 80/100% heating configuration can result in two small volumes of rock, each centered at a wing-heater array, exceeding 300°C at 4 yr. Depending on the percolation flux, the temperature at the springline T_{sp} at the midpoint of the heater drift can exceed 250°C at 4 yr. If it is decided that these temperatures are too high to be representative of coupled T-H-M-C phenomena that will occur under repository thermal loads, it will be necessary to modify the heating rates and/or schedule. Two approaches to reducing temperatures in the DST are considered: (1) reducing the power in the wing-heater arrays, and (2) ramping back the power for both the drift- and wing-heaters after an initial constant-power-heating period.

The first approach begins with a case in which the power is 80% full capacity for both the drift heaters and wing-heater arrays. Table 6.1 and Figure 6.1 summarize the comparison between the 80/100% and 80/80% heating configurations. Although not shown in a figure, the 80/80% configuration results in boiling and dryout zones that tend to slope more toward the lateral edges, thereby allowing more condensate-shedding than is allowed with the 80/100% configuration. Relative to the 80/100% configuration, the 80/80% configuration reduces the peak temperature at the springline of the heater drift by 22°C–24°C (Figure 6.1a) and reduces the maximum rock temperature by 61°C (Figure 6.1b). The 80/80% configuration reduces the vertical thickness of the dryout zone ΔZ_{dry} by approximately 10% (Figure 6.1c) and allows the relative humidity *RH* in the dryout zone to return more quickly to humid conditions (Figure 6.1d). In general, reducing the heating rate in the wing-heater arrays is an

ineffective way to reduce the peak temperature at the springline of the heater drift; however, it is an effective way to reduce the maximum temperature in the rock.

Model calculations for repository thermal-loading conditions show that T-H behavior can be divided into three sequential periods: (1) heat-up/dryout, (2) quasi-steady, and (3) cool-down/rewetting. A DST with a constant-power-heating period followed by a rapid rampdown to zero power will result in the heat-up and cool-down periods, but it cannot result in a quasi-steady period. If the constant-power-heating period is followed with a gradual rampdown of the heater power, it is possible to include a quasi-steady period during the DST. In addition to reducing the maximum drift-wall and rock temperatures, a second motivation for modifying the heating schedule from the constant 80/100% heating configuration is to allow the DST to provide a period of quasi-steady T-H behavior.

A sensitivity analysis was conducted to determine how the heating schedule should be modified to achieve a period of quasi-steady peak temperatures in the vicinity of the heater drift. The springline at the midpoint of the heater drift (i.e., adjacent to the fifth drift heater) was chosen as the target temperature location because it is where the maximum drift-wall temperature occurs along the heater drift. Two cases were considered for target temperatures of 150°C and 200°C, respectively, for ambient percolation fluxes of 0.36 mm/yr and 3.6 mm/yr. The primary objectives of an optimized heating schedule are the following:

- Reach the target temperature as quickly as possible
- Keep as close to the target temperature for as long as necessary to obtain a T-H perturbation sufficient to drive coupled T-H-M-C processes relevant to repository thermal-loading conditions

Obtaining a heating schedule that achieves these objectives is an iterative process. This was begun by iteratively using a two-dimensional model of the DST to obtain a good initial estimate for the subsequent three-dimensional T-H calculation. With a good initial estimate, it was only necessary to repeat the three-dimensional calculation once to obtain the design objectives.

Table 6.1 summarizes the T-H conditions for the 150°C and 200°C target cases and for the constant-power cases. Figures 6.2–6.4 also summarize the T-H conditions for the 150°C and 200°C target cases. All of the target-temperature cases start with the 80/100% heating configuration for an initial constant-power period, and all cases have a steep linear-rampdown period from 4–5 yr. Figures 6.5–6.10 give the three-dimensional distributions of T and S_{liq} for 1, 2, 3, 4, 5, and 10 yr for the 200°C-target case with a percolation flux q_{perc} = 3.6 mm/yr. Figures 6.11–6.16 give the same information for the 150°C-target case with q_{perc} = 3.6 mm/yr. Figures 6.17–6.22 give the same information for the 200°C-target case with q_{perc} = 0.36 mm/yr. Figures 6.22–6.28 give the three-dimensional distributions of T and S_{liq} for 1, 2, 3, 4, 5, and 10 yr for the 200°C-target case with a percolation flux q_{perc}= 0.36 mm/yr.

For a 200°C-target temperature and a 3.6-mm/yr percolation flux, it is possible to maintain a constant 80/100% heating configuration for 2 yr before throttling back on the heater power. From 2–4 yr, the heater power is linearly ramped down from 80/100% to 40/50% full capacity. During the quasi-steady period, T_{sp} ranges from 204°C to 192°C, and T_{wh} ranges from 243°C to 215°C. Relative to the constant-power 80/100% case, the peak T_{wh} is reduced by 60°C, and the peak T_{wh} is reduced by 73°C. In spite of this very large reduction in temperature, the vertical thickness of the dryout zone ΔZ_{dry} is only reduced by approximately 8% at 4 yr. Recall that the 80/80% configuration reduced ΔZ_{dry} by 10%, but achieved a smaller reduction in peak maximum drift-wall and rock temperatures. Therefore, ramping the heating rates back (as is done in the 200°C-target case) is a very effective way to reduce maximum target temperatures and still achieve a large spatial perturbation in T-H conditions.

For a 150°C-target temperature and a 3.6-mm/yr percolation flux, it is possible to maintain a constant 80/100% heating configuration for 1 yr before throttling back on the heater power. At 1 yr, the power is stepped down to 64/80% full capacity. For 1–4 yr, the heater power is linearly ramped down from 64/80% to 32/40% full capacity. During the quasi-steady period, T_{sp} ranges from 157°C to 152°C and T_{wh} ranges from 182°C to 166°C. Relative to the constant-power 80/100% case, T_{wh} is reduced by 107°C, and T_{wh} is reduced by 134°C. However, ΔZ_{dry} is reduced by approximately 30% at 4 yr. For the 150°C-target case, the reduction in maximum temperatures comes at a considerable expense—that is a large reduction in the spatial extent of the T-H perturbation.

For a 200°C-target temperature and a 0.36-mm/yr percolation flux, it is possible to maintain a constant 80/100% heating configuration for 1.25 yr before throttling back on the heater power. From 1.25–1.5 yr, the heater power is linearly ramped down from 80/100% to 76/95% full capacity. From 1.5–4 yr, the heater power is linearly ramped down from 76/95% to 40/50% full capacity. During the quasi-steady period, T_{sp} ranges from 205°C to 195°C, and T_{wh} ranges from 241°C to 219°C. Relative to the constant-power 80/100% case, the peak T_{wh} is reduced by 73°C, and the peak T_{wh} is reduced by 92°C. In spite of the large reduction in maximum drift-wall and rock temperatures, ΔZ_{dry} is only reduced by approximately 15% at 4 yr. As was seen for a 3.6-mm/yr percolation flux, this is a very effective way to reduce maximum target temperatures and still achieve a large spatial perturbation in T-H conditions.

For a 150°C-target temperature and a 0.36-mm/yr percolation flux, it is possible to maintain a constant 80/100% heating configuration for 1 yr before throttling back on the heater power. At 1 yr, the power is stepped down to 56/70% full capacity. For 1–4 yr, the heater power is linearly ramped down from 56/70% to 28/35% full capacity. During the quasi-steady period, T_{sp} ranges from 158°C to 152°C and T_{wh} ranges from 182°C to 165°C. Relative to the constant-power-80/100% case, T_{wh} is reduced by 120°C, and T_{wh} is reduced by 151°C. However, ΔZ_{dry} is reduced by approximately 30% at 4 yr. As was seen for a 3.6-mm/yr percolation flux, the reduction in maximum temperatures comes at a considerable expense—that is a large reduction in the spatial extent of the T-H perturbation.

In general, for all cases it was possible to stay within 8°C of the target temperature during the quasi-steady period. While the 200°C-target cases result in considerably lower springline temperatures than do the constant-power cases, the reduction in ΔZ_{dry} is relatively minor. This is in sharp contrast to the 150°C-target cases, which result in a very large reduction in ΔZ_{dry} relative to the constant-power cases. In general, the 200°C-target cases facilitate an effective trade-off between perturbing a sufficiently large volume of rock and not driving peak temperatures excessively high.

Table 6.1.

Temperature in the rock at the springline T_{sp} and at the hottest wing-heater location T_{wh}, and vertical dryout zone thicknesses ΔZ_{dry} at the central longitudinal (i.e., axial) location of the drift-scale test for various heating schedules and values of ambient percolation flux q_{perc}.

Heating schedule (percentage of full drift/wing-heater capacity) (ramp down to 0/0% power at 5 yr)	q_{perc} (mm/yr)	T_{sp}/T_{wh} (°C) (2 yr)	T_{sp}/T_{wh} (°C) (peak)	T_{sp}/T_{wh} (°C) (4 yr)	ΔZ_{dry} (m) (2 yr)	ΔZ_{dry} (m) (4 yr)
0–4 yr: 80/100%	3.6	189/236	264/316	264/316	10.3	17.6
0–2 yr: 80/100% 2–4 yr: 80/100% to 40/50%	3.6	189/236	204/243	192/215	10.3	16.3
0–1 yr: 80/100% 1–4 yr: 64/80% to 32/40%	3.6	152/180	157/182	152/166	8.9	12.7
0–4 yr: 80/80%	3.6	177/190	240/255	240/255	9.7	15.9
0–4 yr: 80/100%	0.36	206/257	278/333	278/333	11.4	17.9
0–1.25 yr: 80/100% 1.25–1.5 yr: 80/100% to 76/95% 1.5–4 yr: 76/95% to 40/50%	0.36	194/237	205/241	195/219	11.2	15.2
0–1 yr: 80/100% 1–4 yr: 56/70% to 28/35%	0.36	155/182	158/182	152/163	9.7	12.7
0–4 yr: 80/80%	0.36	193/209	255/272	255/272	10.6	15.8

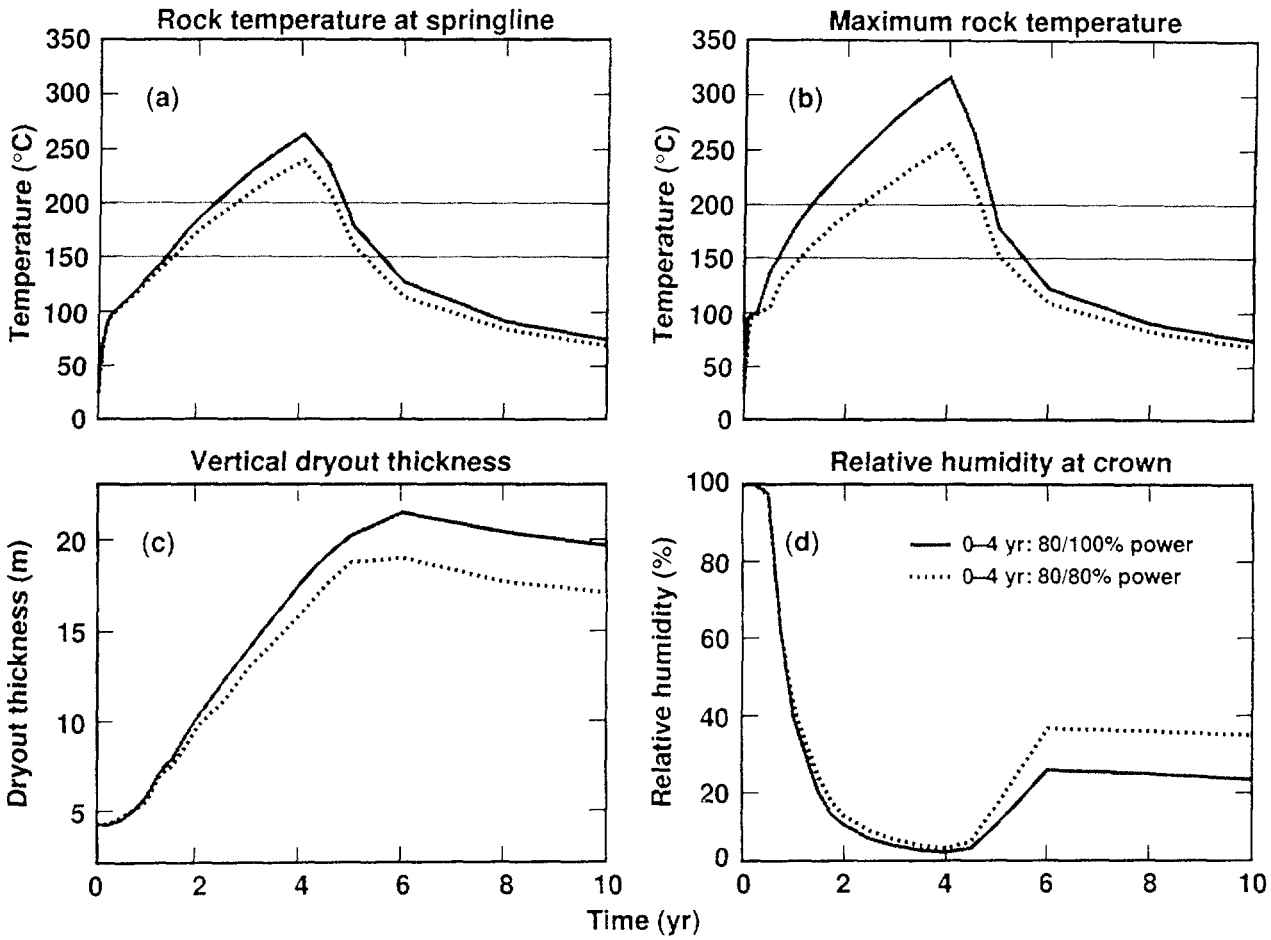

Fig. 6.1. Thermal-hydrological conditions are given at locations in a plane transverse to the midpoint of the heater drift for two constant-power-heating cases and percolation flux = 3.6 mm/yr. The listed power percentages are for the drift heaters and wing-heater arrays, respectively, relative to full capacity. The heater power is constant for 0–4 yr, followed by a linear rampdown to zero power at 5 yr. Plotted are (a) drift-wall temperature T_{sp} at the springline, (b) maximum rock temperature T_{wh}, which occurs at a location that is one-third of the way from the outer edge of the wing-heater array, (c) vertical dryout zone thickness ΔZ_{dry}, and (d) relative humidity RH_{cr} in the rock at the crown of the heater drift. TB-6/5/97-Fig.6.1

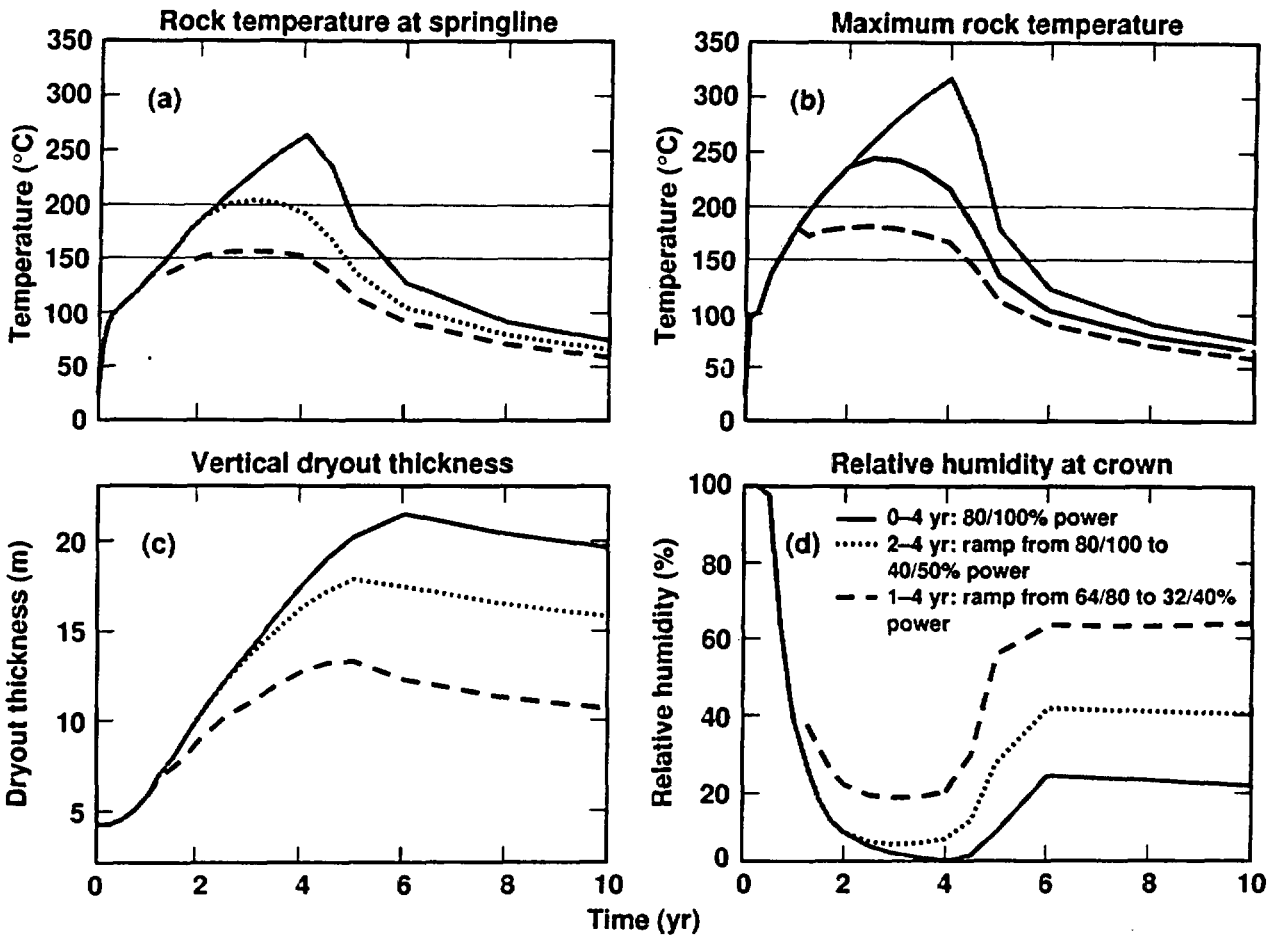

Fig. 6.2. Thermal-hydrological conditions are given at locations in a plane transverse to the midpoint of the heater drift for three heating-schedule cases and percolation flux = 3.6 mm/yr. The listed power percentages are for the drift heaters and wing-heater arrays, respectively, relative to full capacity. The initial heater power is 80/100% of full capacity. For 4–5 yr, the power is linearly ramped to zero power. Plotted are (a) drift-wall temperature T_{sp} at the springline, (b) maximum rock temperature T_{wh}, which occurs at a location that is one-third of the way from the outer edge of the wing-heater array, (c) vertical dryout zone thickness ΔZ_{dry}, and (d) relative humidity RHcr in the rock at the crown of the heater drift.

TB-6/5/97-Fig.6.2

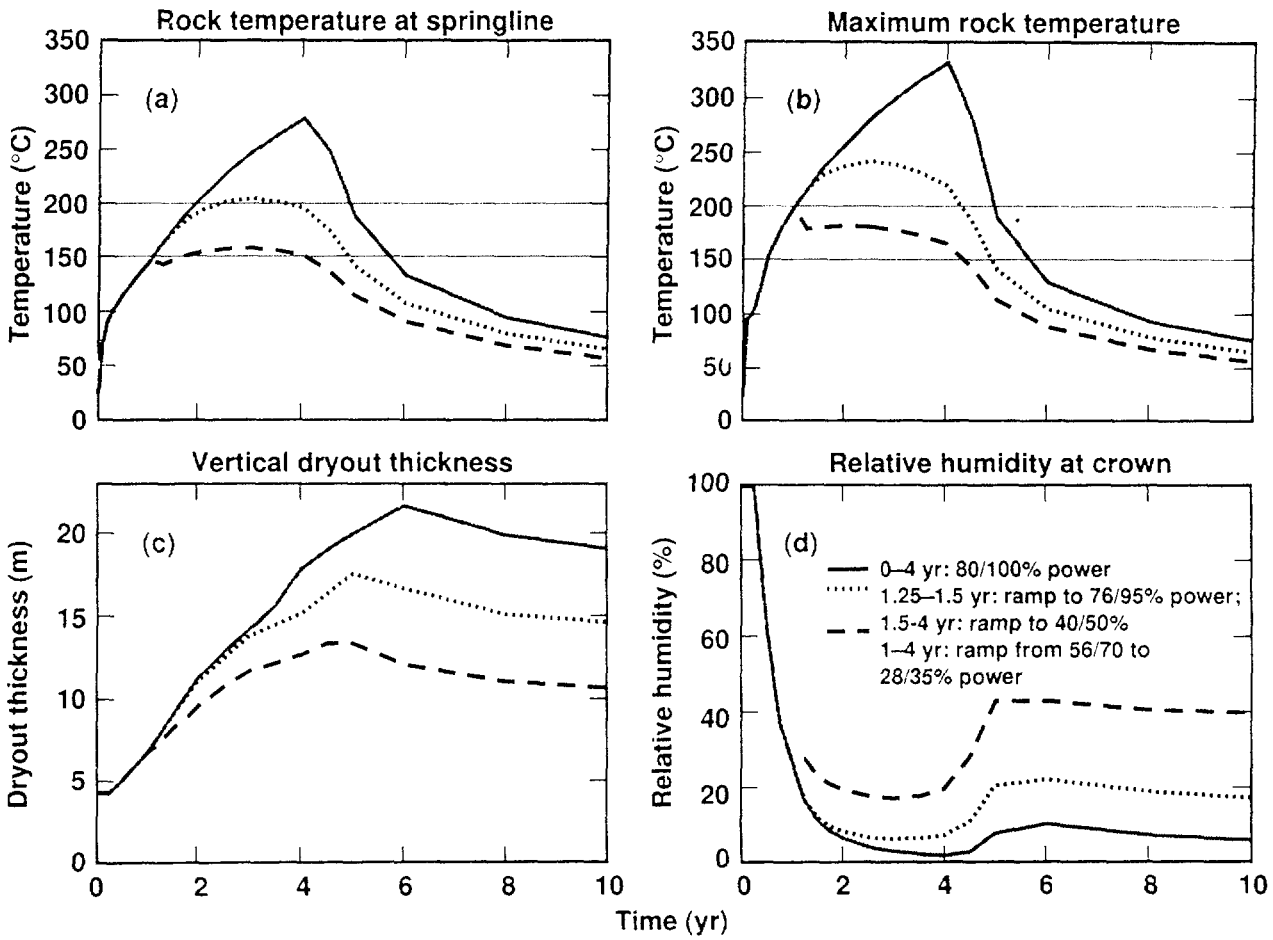

Fig. 6.3. Thermal-hydrological conditions are given at locations in a plane transverse to the midpoint of the heater drift for three heating-schedule cases and percolation flux = 0.36 mm/yr. The listed power percentages are for the drift heaters and wing-heater arrays, respectively, relative to full capacity. The initial heater power is 80/100% of full capacity. For 4–5 yr, the power is linearly ramped to zero power. Plotted are (a) drift-wall temperature T_{sp} at the springline, (b) maximum rock temperature T_{wh}, which occurs at a location that is one-third of the way from the outer edge of the wing-heater array, (c) vertical dryout zone thickness ΔZ_{dry}, and (d) relative humidity RH_{cr} in the rock at the crown of the heater drift.

TB-6/5/97-Fig.6.3

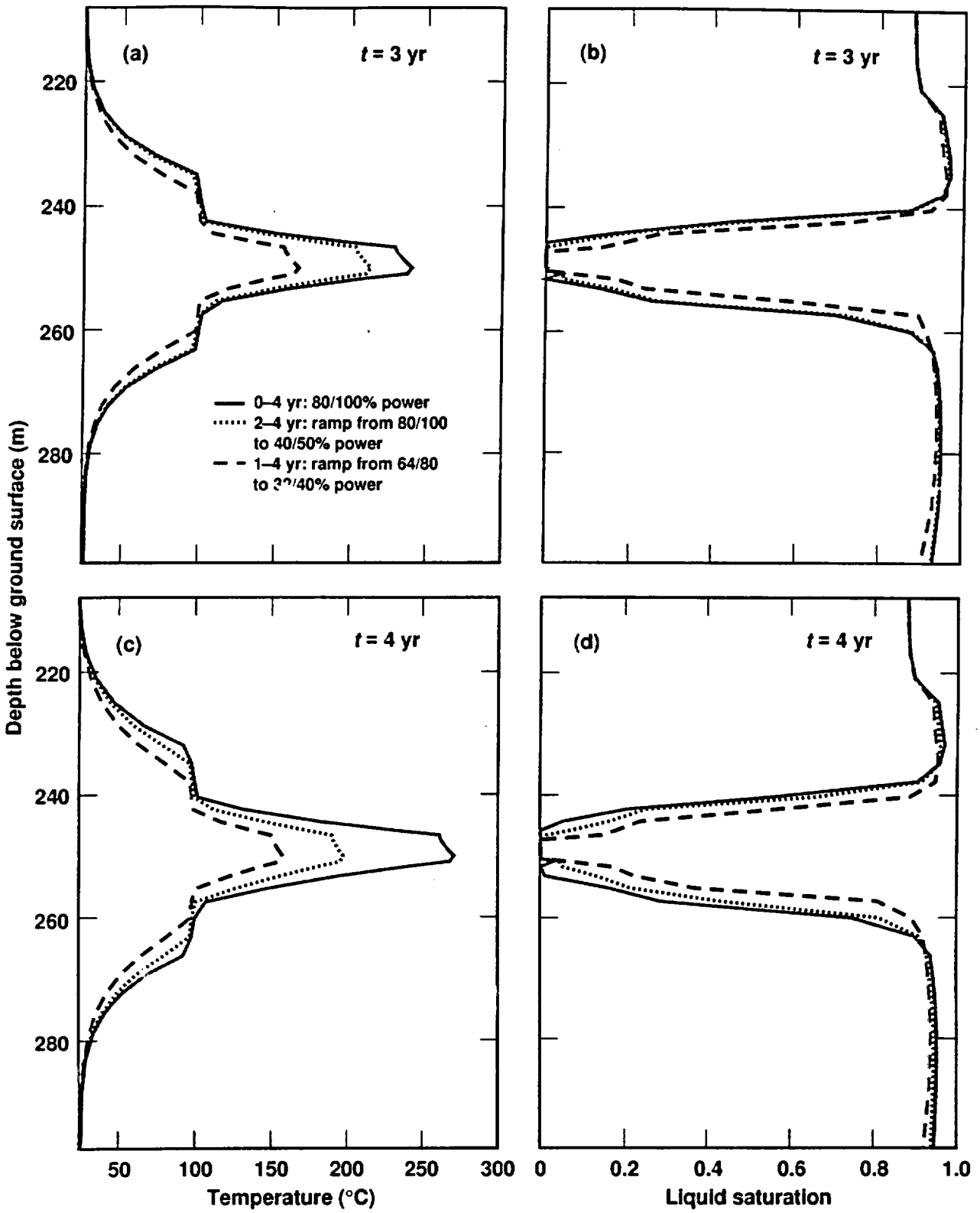

Fig. 6.4. Vertical temperature profile at the midpoint of the heater drift is plotted for (a) 3 yr and (c) 4 yr and three heating-schedule cases. Percolation flux = 3.6-mm/yr. Also plotted at the same location is the liquid saturation for (b) 3 yr and (d) 4 yr. The listed power percentages are for the drift heaters and wing-heater arrays, respectively, relative to full capacity. The initial heater power is 80/100% of full capacity. For 4–5 yr, the power is linearly ramped to zero power. TB-6/5/97-Fig.6.4

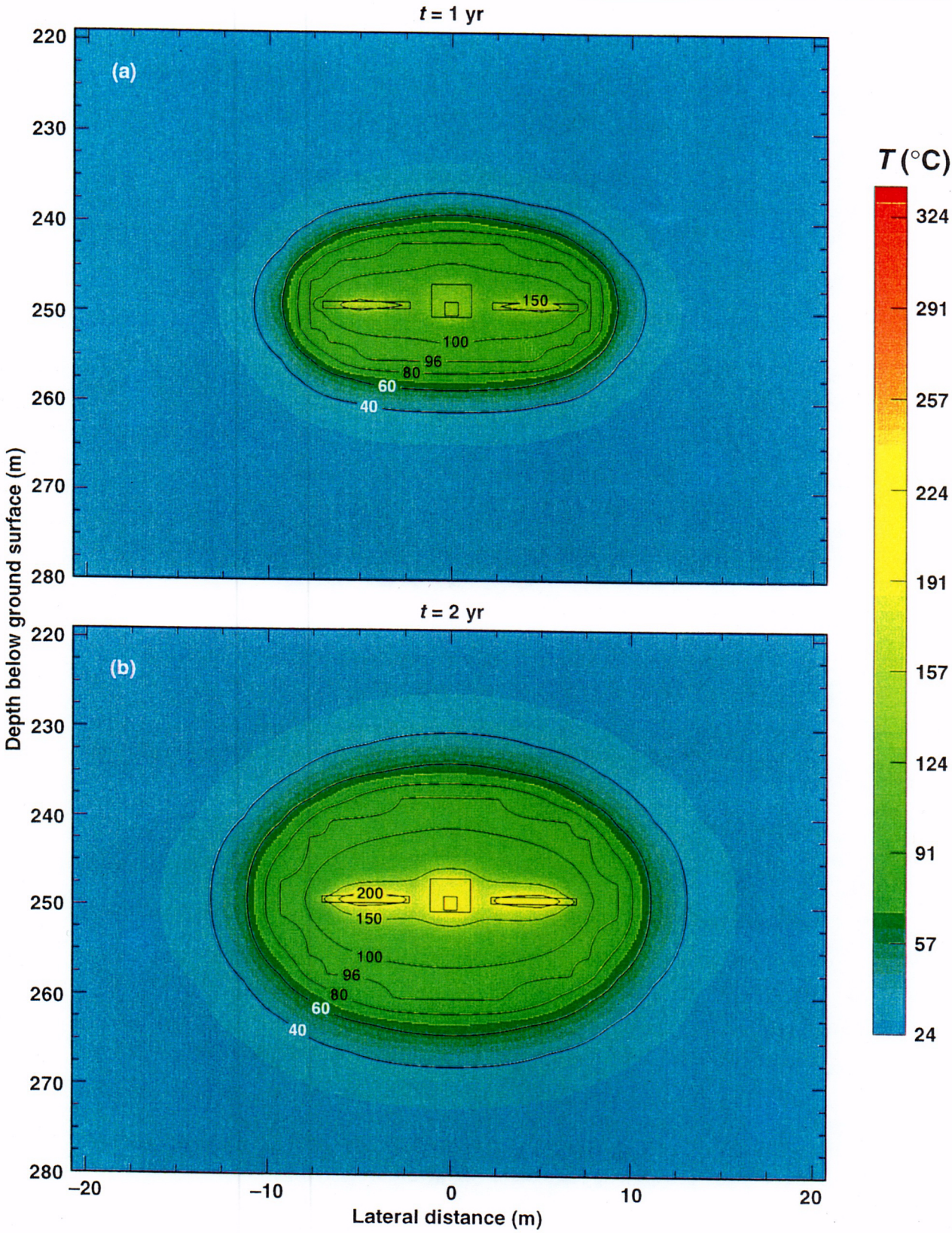

Fig. 6.5. Temperature *T* distribution at (a) 1 and (b) 2 yr in a vertical plane transverse to the midpoint of the heater drift for 3.6-mm/yr percolation flux. The initial drift/wing-heater power is 80/100% of full capacity. For 2–4 yr, the power is linearly ramped from 80/100 to 40/50% of full capacity. For 4–5 yr, the power is linearly ramped down to 0/0%.

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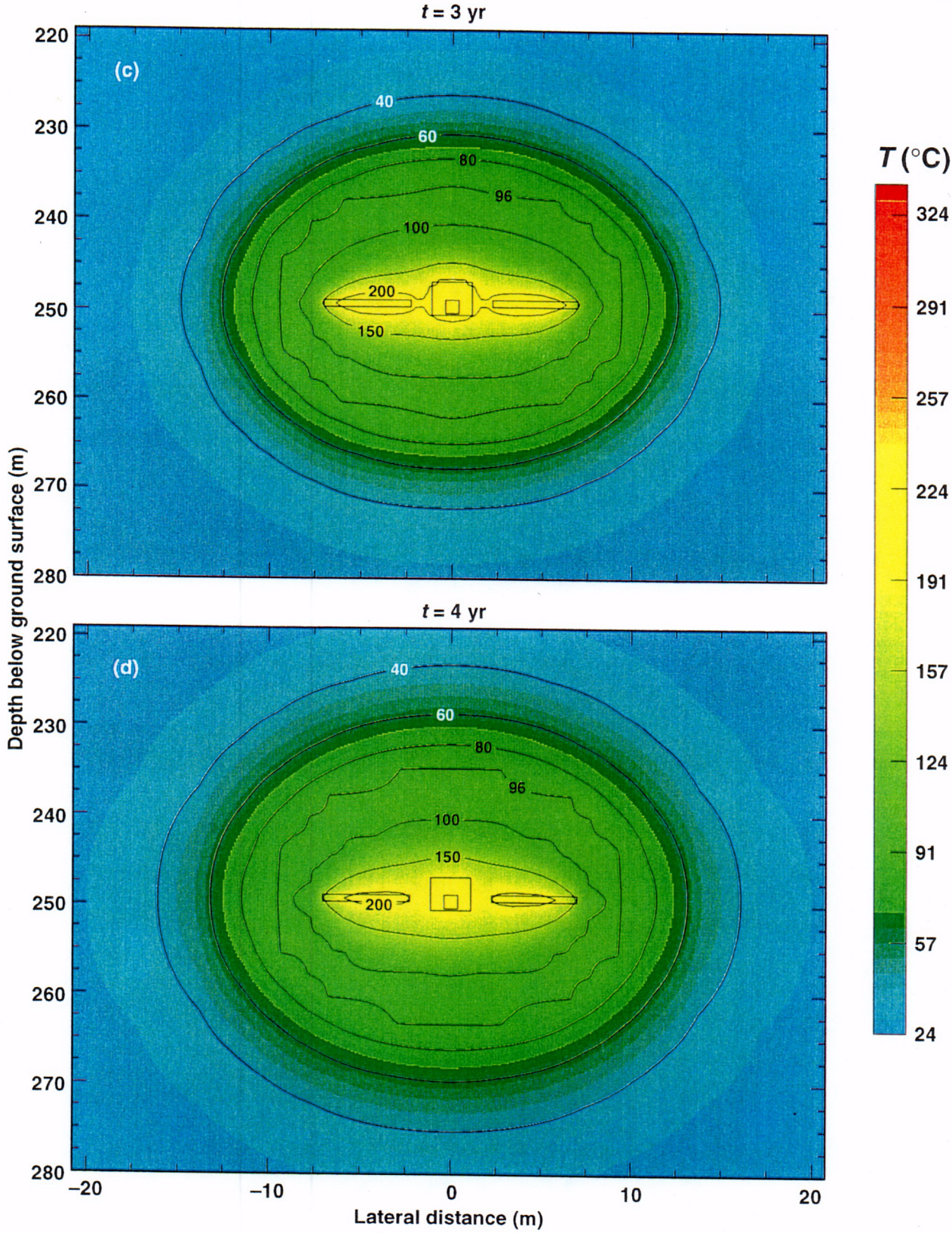

Figure 6.5. Temperature *T* distribution at (c) 3 and (d) 4 yr in a vertical plane transverse to the midpoint of the heater drift for 3.6-mm/yr percolation flux. The initial drift/wing-heater power is 80/100% of full capacity. For 2–4 yr, the power is linearly ramped from 80/100 to 40/50% of full capacity. For 4–5 yr, the power is linearly ramped down to 0/0%.

TB-6/5/97-T36at_zx.3-4y

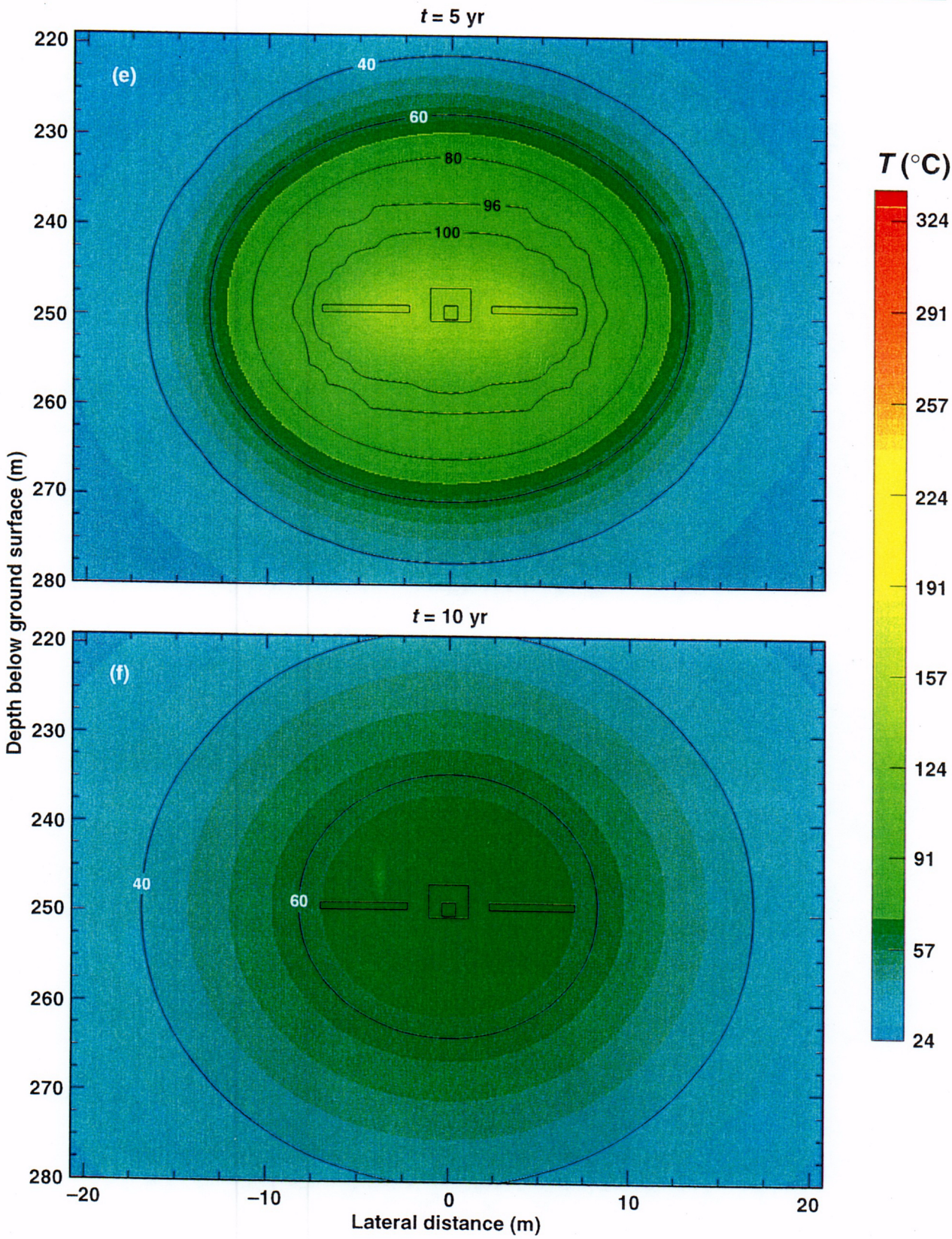

Figure 6.5. Temperature *T* distribution at (e) 5 and (f) 10 yr in a vertical plane transverse to the midpoint of the heater drift for 3.6-mm/yr percolation flux. The initial drift/wing-heater power is 80/100% of full capacity. For 2–4 yr, the power is linearly ramped from 80/100 to 40/50% of full capacity. For 4–5 yr, the power is linearly ramped down to 0/0%.

TB-6/5/97-T36at_zx.5-10y