Figure 1: Reference current source circuit; $V_{DD} = 5$ V, $V_{SS} = -5$ V, $V_{REF} = 1$ V; $M_1$ and $M_2$ are two identical NMOS transistors; in the active/saturation region the drain current is given by: $I_D = K(V_{GS} - V_t)^2$, where $V_t = 1$ V, $K = 100$ $\mu$A/V$^2$.

(a) [1] In Fig.1, label + and - inputs of the op-amp so that the circuit operates as a reference current source.

(b) [2] Assuming that all components are ideal and that $M_1$ and $M_2$ operate in the active/saturation region, find an expression for $I_{REF}$. Find $R$ so that $I_{REF} = 100$ $\mu$A.

$$I_{REF} = \frac{V_{REF}}{R}, \quad R = 10 \text{ k}\Omega$$

 Since $H_1$, $H_2$ are in act/sat. The current mirror $H_1-M_2$ gives $I_{REF} = I_{D1}$

(c) [2] Suppose that all components are ideal, except that the op-amp input offset voltage is $V_{OS} = \pm 5$ mV. Find the relative tolerance $\Delta I_{REF}/I_{REF}$

$$\frac{I_{REF}}{I_{REF}} = \frac{V_{REF} + V_{OS}}{V_{REF}}, \quad \frac{\Delta I_{REF}}{I_{REF}} = \frac{R}{V_{REF}} \frac{\Delta V_{REF}}{V_{OS}} \frac{V_{OS}}{V_{REF}} = \frac{\pm 5 \text{ mV}}{4 \text{ V}} = \pm 0.5 \%$$

(d) [2] Suppose that temperature drifts in all components except $R$ can be neglected. Assuming $T_C(R) = 2000$ ppm/$^\circ$C, find $T_C(I_{REF})$.

$$T_C(I_{REF}) = \frac{T_C(R)}{T_C(I_{REF})} = -\frac{\Delta I_{REF}}{I_{REF}} \frac{1}{\Delta R} = -\frac{R}{V_{REF}} \frac{\Delta V_{REF}}{V_{OS}} \frac{V_{OS}}{V_{REF}} \frac{\Delta R}{R} = -\frac{R}{T_C(R)} = -2000 \text{ ppm/}^\circ\text{C}$$

(e) [1] Is it necessary for the op-amp in Fig. 1 to have a rail-to-rail output voltage swing? (Just answer YES or NO, there is no need to justify the answer)

NO.  

$$V_{GS} = V_t + \frac{\sqrt{I_{REF}/K}}{2} = 2 \text{ V}, \quad \text{So} \quad V_G \text{ is well above } -V_{SS} \text{ and well below } +V_{DD}$$

(f) [1] Is it necessary for the op-amp in Fig. 1 to have a rail-to-rail input common mode voltage range? (Just answer YES or NO, there is no need to justify the answer)

NO.  

$$V(+) = V(-) = \frac{V_{PD2}}{2} = V_t, \quad V_G = -V_{SS} + V_{OS} = -V_{SS} + V_t + \sqrt{\frac{I_{REF}}{K}} = -3 \text{ V}$$

(g) [1] Find the maximum value of $R_L$ such that $I_{REF} = 100$ $\mu$A.

Triode boundary: $V_{PD2} = V_t$, $V_G = -V_{SS} + V_{OS} = -V_{SS} + V_t + \sqrt{\frac{I_{REF}}{K}} = -3 \text{ V}$

$$V_{PD2} = V_t, \quad V_G = -V_{SS} + V_{OS} = -V_{SS} + V_t + \sqrt{\frac{I_{REF}}{K}} = -3 \text{ V}$$

$$R_{L_{max}} = \frac{V_{PD} - V_{PD2}}{I_{REF}} = \frac{9 \text{ V}}{100 \mu\text{A}} = 90 \text{ k}\Omega$$