AN316

Application note

TVS clamping protection mode

Introduction

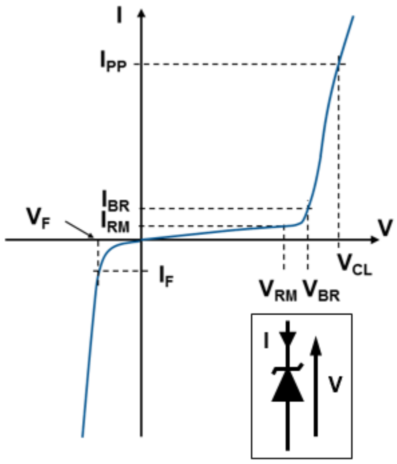
The transient voltage suppressor (TVS) is an avalanche diode specially designed to clamp overvoltage and dissipate high transient power. TVS must be selected in two ways:

1. Check that the circuit operating conditions do not exceed the specified limit of the component.
   – For non-repetitive surge operation
   – For repetitive surge operation
   – For normal operation
2. Check that the maximum value of the clamped voltage under the worst conditions corresponds to the specification of the circuit to protect.

1 Review of TVS characteristics

Figure 1. **Electrical characteristics - parameter definitions**

V_{RM}	Maximum stand-off voltage
I_{RM}	Maximum leakage current @ V_{RM}
V_R	Stand-off voltage
I_R	Leakage current @ V_R
V_{BR}	Breakdown voltage @ I_{BR}
I_{BR}	Breakdown current
V_{CL}	Clamping voltage @ I_{PP}
I_{PP}	Peak pulse current
R_D	Dynamic resistance
V_F	Forward voltage drop @ I_F
I_F	Forward current
αT	Voltage temperature coefficient



1.1 Stand-off voltage

V_{RM} is the maximum voltage that TVS can withstand in normal operation. Normal operating voltage must be lower than V_{RM}.

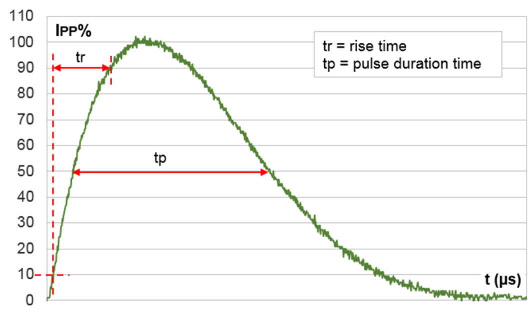
1.2 The breakdown voltage or knee voltage

V_{BR} is the voltage value above which the current in TVS increases very fast for a slight increase in voltage. The breakdown voltage V_{BR} is specified at 25 °C and its temperature coefficient is positive.

1.3 The clamping voltage

V_{CL} as specified in the datasheets is the maximum value for a "standard" current pulse with a peak value of I_{PP} (Figure 2), specified for any type of TVS. If TVS is subjected to a different exponential pulse duration, the value of V_{CL} can be calculated using the application note AN575 or getting the dynamical resistance with the curve given in ST TVS family datasheets "Dynamic resistance versus pulse duration".

Figure 2. **Pulse definition for electrical characteristics**

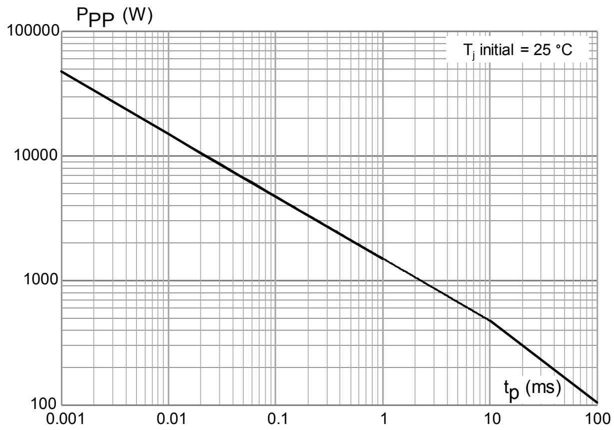


2 TVS peak power dissipation

TVS goal is to protect equipment against transient disturbances. The duration of these transients is linked to the application where the TVS operates. For example, electrostatic discharge (ESD) durations are in the range of tens of nanoseconds while other surges durations can vary from tens of microseconds for industrial application, to hundreds of microseconds for telecom and even tens of milliseconds for automotive standards.

TVS performances are given in the datasheet for both 8/20 µs and 10/1000 µs waveforms (V_{CL}, I_{PP}). Additionally the peak pulse power versus pulse duration curve (see Figure 3) allows the designer to select the right TVS for the specific pulse duration of her/his application.

Figure 3. Maximum peak pulse power versus exponential pulse duration for SM15T series

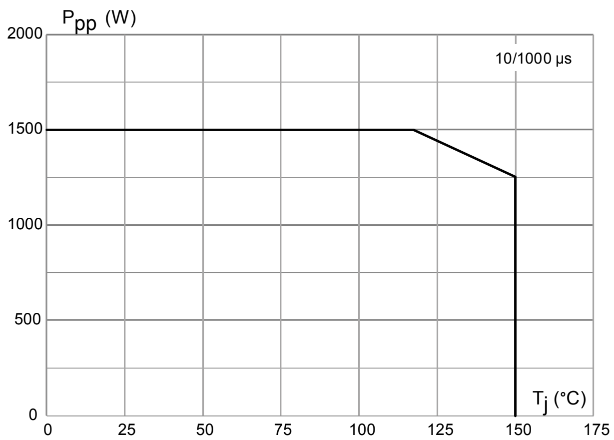


- Peak pulse power calculation versus exponential pulse duration

$$P_{PP} = V_{CL} \times I_{PP} \quad (1)$$

If the initial temperature exceeds 25 °C, a power derating is applied in accordance with the curve of Figure 4, which is available for all TVS datasheets.

Figure 4. Maximum peak power dissipation versus initial junction temperature for SM15T series

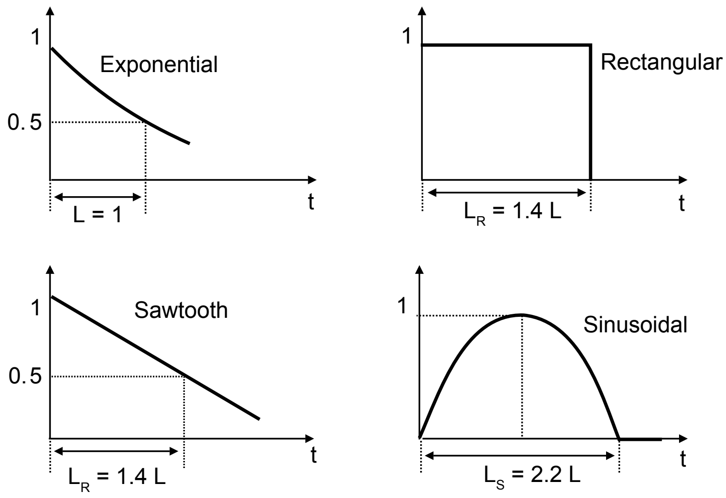


Peak power capability at 150 °C remains at high level: P_{PP} = 1250 W (83% of peak power at 25 °C).

If the current through the TVS is not exponential, the diagrams of Figure 5 gives the multiplication factor to calculate the equivalent exponential pulse duration.

For example, to get equivalent exponential pulse duration of a rectangular surge, the square duration needs to be divided by 1.4.

Figure 5. Pulse duration equivalence factors for same power dissipation



3 TVS average power dissipation

In repetitive operation, the specification to be considered is average power (P_{AV}). It is calculated (Eq. (2)) from the surge frequency (f) and the energy dissipated during each pulse (W).

$$P_{AV} = f \times W \tag{2}$$

The junction temperature (T_j) calculated from this average power should never exceed the specified maximum junction temperature. This temperature is calculated (Eq. (3)) from the thermal resistance ($R_{th(j-a)}$), ambient temperature (T_{amb}) and average power (P_{AV}), exactly like for a rectifier diode.

$$T_j = T_{amb} + R_{th(j-a)} \times P_{AV} \tag{3}$$

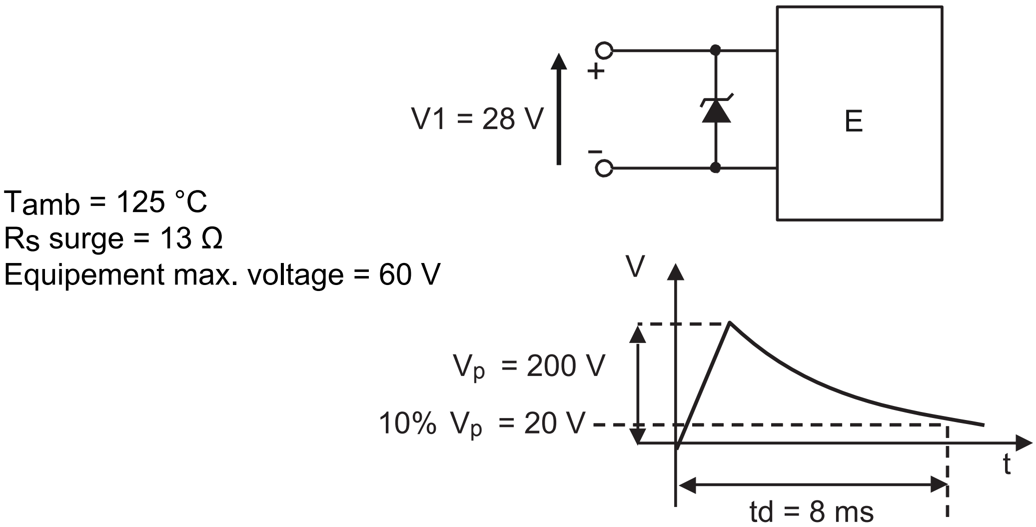
4 How to size a TVS

4.1 Non-repetitive surges

Let’s take an example: a source (V1) with a rated voltage of 28 V supplies equipment E, which has to be protected against over voltages. This source is subjected to random non-repetitive exponential overvoltage with an amplitude of 200 V and a duration of 8 ms (td) at 10% of peak voltage (standard wave - see Figure 6).The equivalent internal impedance Z of the surge source is 13 Ω.

The maximum ambient temperature is 125 °C. In no circumstance, equipment E must be subjected to a voltage higher than 60 V.

Figure 6. Protected equipment and surge



4.1.1 TVS selection

We assume that supply voltage V1 = 28 V varies by ± 15%, i.e. between around 23.8 V and 32.2 V. The protection voltage V_{RM} of the TVS should then be greater than or equal to 32.2 V.

4.1.2 Predetermination of the peak power P_{PP} and t_P value

Equipment E cannot withstand a voltage above 60 V so $V_{CL} \leq 60$ V.

Assuming that there is a TVS that meets this criterion, an initial calculation of the TVS power can be made:

$$P_{PP} = V_{CL} \times I_P \text{ where } I_{PP} = \frac{V_P - V_{CL}}{Z} = \frac{200\ \text{V} - 60\ \text{V}}{13\ \ \Omega} \approx 10.8\ A \quad (4)$$
$$P_{PP} = 55\ \ V \times 10.8\ \ A = 648\ \ W$$

This power corresponds to an operating temperature of 125 °C. The datasheets indicate the power at 25 °C, so we have to correct the power according to the curves of admissible power versus initial temperature (Figure 4):

- at 125 °C, power capability is around 1440 W, so ratio is

$$\frac{1440\ W}{1500\ W} = 0.96$$

To estimate the t_p value (definition in Figure 2), we need to define by calculations the current through TVS during the pulse. These calculations have been developed in Section Appendix A . We obtain t_p = 2 ms.

From the calculated P_{PP} (Eq. (4)) and t_p values (Section Appendix A) and with “Maximum peak pulse power versus exponential pulse duration” curve given in each TVS family, we can check the suitable TVS family with the calculated peak power.

From Figure 3 and t_p = 2 ms, SM15T maximum power capability is 1000 W at 25°C. Applying the derating for the temperature gives P_{PP} = 1000 W * 0.96 = 960 W at 125°C.

SM15T is suitable for this application example, as dissipated peak power at 125°C is equal to 648 W.

Note: The SM6T power capability is lower than 400 W for t_p = 2 ms and T_j =125 °C, therefore it is not suitable in this example.

4.1.3 Selection of the TVS

We can now establish an initial specification of the TVS to use.

- $V_{RM} \geq 32.2$ V
- $V_{CL} \leq 60$ V for I_p = 10.8 A
- P_{PP} (125 °C) = 648 W for t_p = 2 ms, corresponding to:

$$Ppp\left(25°C\right) = \frac{648}{0.96} = 675\ \ W \quad (5)$$

The ST TVS type corresponding to these characteristics is the SM15T39A.

Below its characteristics:

- Power capability: 1500 W at 10/1000 µs exponential current waveform
- V_{RM} = 33.3 V
- V_{BR} min. = 37.1 V
- V_{BR} typ. = 39 V
- V_{BR} max. = 41 V
- V_{CL} max. = 53.9 V for I_{pp} = 28 A at 10/1000 µs exponential current waveform
- R_D max. = 0.461 Ω at 10/1000 µs exponential current waveform
- $\alpha T = 10.10^{-4}$/°C

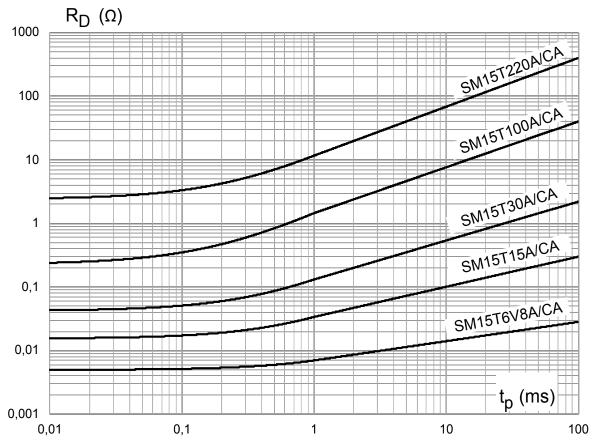
4.1.4 Determination of the clamping voltage V_{CL}

To determine V_{CL} at I_P = 10.8 A, we use the equation:

$$V_{CL} = V_{BR} + R_D \cdot I_P$$

R_D can be estimated using the Figure 7. Dynamic resistance versus pulse duration curves.

Figure 7. Dynamic resistance versus pulse duration



SM15T39A is not plotted on Figure 7. However, we will use the SM15T30A, showing a ratio ≈ 2 between R_D at 1 ms and R_D at 2 ms.

Maximum R_D of SM15T39A at 1 ms = 0.461 Ω, so maximum R_D at 2 ms calculation gives 0.922 Ω.

$$V_{CL}\ typ. = V_{BR}\ typ. + R_D\ typ.\left(at\ t_p = 2\,ms\right) \times I_P = 41\,V + 0.992\ \Omega \times 10.8\ A = 51\,V \quad (6)$$

4.1.5 Temperature correction

The maximum clamping voltage at maximum ambient temperature 125 °C is:

$$V_{CL}\left(T_j\right) = V_{CL}\left(25°C\right) \times \left(1 + \alpha T \times \left(T_j - 25°C\right)\right) \quad (7)$$

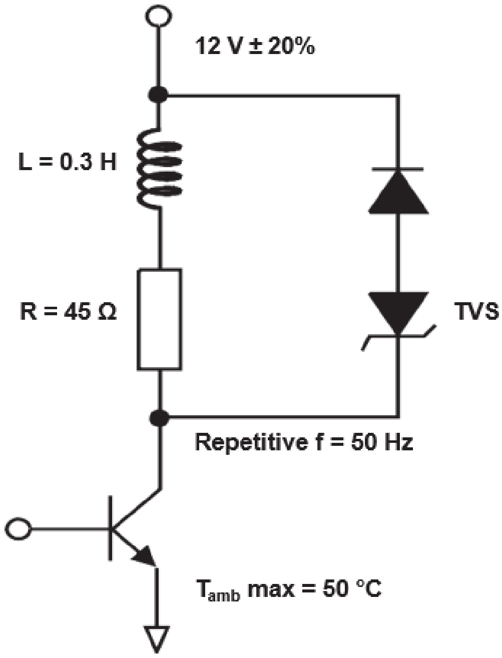
Maximum V_{CL}(125 °C) = 51 x (1 + 10.10^{-4} x (125-25)) = 56.1 V, below the 60 V limit.

SM15T39A is suitable in terms of power capability and, during surges, the clamping voltage is lower than the maximum voltage admissible by the circuit to protect, even with the worst case TVS parameters.

4.2 Repetitive surges

In other application, electronic circuits need to be protected against repetitive surges. Let’s take the following example, where we have to protect the transistor shown in Figure 8 with a TVS having clamping voltage V_{CL} that does not exceed 90 V.

Figure 8. Transistor protection



For this usual topology, each time the transistor turns off, a spike (called later V_{spike}) is generated due to the inductive effect. This spike reaches very high voltage value and would damage the transistor if no protection is implemented.

4.2.1 Calculation method

We consider $V_{CL} \approx V_{BR}$ due to low current through TVS in comparison with TVS capability current value.

Experience shows that this hypothesis is confirmed in most of the cases with a TVS protecting a switch. Therefore, the TVS should be initially selected according to its thermal characteristics.

P_{AV} is the average power dissipated through the TVS.

An approximated value can be obtained by supposing that the TVS absorbs the whole energy contained in the inductance. This hypothesis is realistic when the ratio $\frac{\mathrm{V_{spike}}}{\mathrm{VBR}}$ is significant.

Average power is calculated with Eq. (8) for the maximum supply voltage (nominal voltage value + 20% = 12 V + 2.4 V)

$$P_{AV} = \frac{1}{2} x\ L\ x\ I^2\ x\ f = \frac{1}{2} x\ 0.2\ H\ x \left(\frac{12\ V + 2.4\ V}{45\ \Omega}\right)^2 x\ 50\ Hz = 0.512\ W \tag{8}$$

Let’s try with ST product type SMA6J70A.

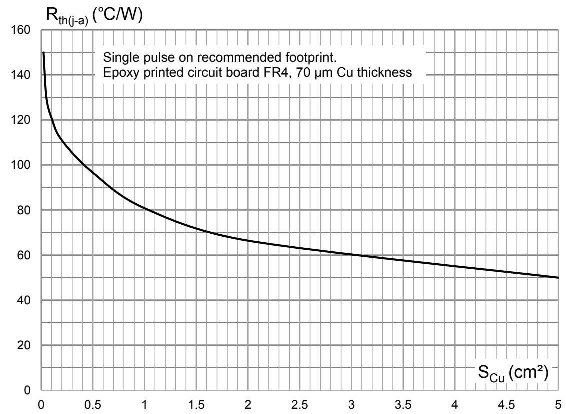
4.2.2 First attempt

Below its characteristics:

- Power capability: 600 W at 10/1000 µs exponential current waveform
- V_{RM} = 70 V
- V_{BR} min. = 77.8 V
- V_{BR} typ. = 81.9 V
- V_{BR} max. = 86 V
- V_{CL} max. = 110 V for I_{PP} = 5.5 A at 10/1000 µs exponential current waveform
- R_D max. = 4.38 Ω at 10/1000 µs exponential current waveform
- $\alpha T = 10.5 \times 10^{-4}$/°C
- $R_{th(j-a)}$ = 150 °C/W (see Figure 9 below)

Maximum junction temperature T_j = 150 °C

Figure 9. Thermal resistance junction to ambient versus copper area under each lead



4.2.2.1 T_j calculation

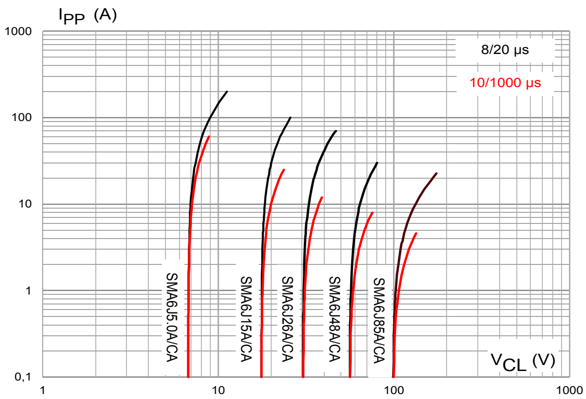
$$T_J = T_{amb} + P_{AV} \times R_{th(j-a)} = 50\ °C + 0.512\ W \times 150°C/W = 126.8°C \quad (9)$$

This value is compatible with the TVS characteristics as 126.8 °C calculated is lower than 150 °C, maximum junction temperature given in SMA6J datasheet.

4.2.2.2 *Determination of the V_{CL}*

For such a low current level through TVS ((12 V + 2.4 V) / 45 Ω = 0.32 A), clamping voltage is very close to V_{BR} value as shown on Figure 10.

Figure 10. Maximum clamping voltage versus peak pulse current



4.2.2.3 *Temperature correction*

We consider SMA6J70A with V_{CL} = V_{BR} max = 86 V.

$$V_{CL}(T_j) = V_{CL}(25°C) \times (1 + \alpha T \times (T_j - 25°C)) \tag{10}$$

V_{CL}(126.8 °C) = 86 V x (1 + 10.5.10^{-4} x (126.8 °C-25 °C)) = 95.2 V

This value V_{CL} is too high. Let's try another TVS.

4.3 Second attempt

To reduce clamping voltage, we need to choose a TVS with a lower V_{BR}, while keeping the V_{RM} ≥ 14.4 V (12 V + 2.4 V).

Let's select then SMA6J58A with below characteristics:

- V_{RM} = 58 V
- V_{BR} max = 71.2 V
- αT = 10.4.10^{-4}/°C

$$V_{CL}(T_j) = V_{CL}(25°C) \times (1 + \alpha T \times (T_j - 25°C)) \tag{11}$$

V_{CL}(126.8 °C) = 71.2 V x (1 + 10.4.10^{-4} x (126.8 °C-25 °C)) = 78.8 V

The SMA6J58A TVS is suitable for this application.

5 Conclusion

TVS protect ICs against over-voltage and other stresses. From the constraints of the application environment (type of surge, maximum ambient temperature, maximum voltage admissible by circuit to protect,…), this application note shows, through examples, how to size the TVS power capability, to calculate the maximum clamping voltage for both single pulse and repetitive pulses. This allows to choose the correct TVS power family and stand-off voltage.

After, this first step, measurements in the real application conditions are mandatory to confirm that the selected TVS is suitable.

Appendix A t_p calculation

Pulse duration time is defined with Figure 2. This type of pulse corresponds to most of the standards used for the protection device. This duration time is defined at 50% of exponential peak current through TVS when surge is applied.

From surge voltage definition given in Figure 6 (i.e. td defined at 10% of peak), and to simplify, we take into account the exponential decreasing voltage only, given with Eq. (12).

$$v(t) = V_p \times e^{-t/\tau} \tag{12}$$

We can calculate the constant time Tau (τ) with Eq. (13) and Eq. (14) .

$$v(td) = 10\% \times V_p = V_p \times e^{-td/\tau} \tag{13}$$

$$\tau = -\frac{td}{\ln 0.1} = -\frac{8\ \text{ms}}{\ln 0.1} = 3.47\ \text{ms} \tag{14}$$

When the surge is applied on the TVS, the current flows through it only when v(t) is higher than V_{BR}. Current formula is given by Eq. (15).

$$i(t) = \frac{v(t) - V_{BR}}{Z} = \frac{Vp \times e^{-t/\tau} - V_{BR}}{Z} \tag{15}$$

where V_{BR} is the breakdown voltage of TVS used and Z is the impedance of surge source. Then, we can calculate the tp value with Eq. (16) and Eq. (17). For tp value, i(tp) = Ip / 2

$$i(tp) = \frac{Ip}{2} = \frac{Vp \times e^{-tp/\tau} - V_{BR}}{Z} \tag{16}$$

$$tp = -\tau \times \ln\left(\frac{Z \times \frac{Ip}{2} + V_{BR}}{Vp}\right) = -3.47\ \text{ms} \times \ln\left(\frac{13\ \Omega \times \frac{10.8\ \text{A}}{2} + 40\ \text{V}}{200\ \text{V}}\right) \approx 2\ \text{ms} \tag{17}$$

Where I_p is the peak current already calculated (11 A) in Section 4.1.2 and as defined in Section 4.1.1 , V_{BR} = 40 V (to get $V_{RM} \geq$ 32V).

Revision history

Table 1. Document revision history

Date	Version	Changes
Oct-2001	3	Previous version
29-Jul-2014	4	Updated for new products.
03-May-2021	5	Updated Figure 1, Figure 2, Figure 3, Figure 4 and Section 4 . Inserted Section Appendix A . Minor text changes.
14-Jun-2022	6	Updated Figure 3, Figure 4, Figure 7, Figure 9. Thermal resistance junction to ambient versus copper area under each lead and Figure 10. Maximum clamping voltage versus peak pulse current . Minor text changes.

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