MAXIMUM CONVERSION EFFICIENCY OF THERMIonic HEAT TO ELECTRICITY CONVERTERS USING PURE TUNGSTEN AS THE EMITTER: A THEORETICAL REVIEW

ABUBAKAR ALKASIM AND ADAM USMAN

(Received 12 August 2009; Revision Accepted 29 March 2010)

ABSTRACT

In this work, analysis of the efficiency of a thermionic converter of heat to electricity is made in terms of the potential difference between the top of the potential barrier in the inter electrode space and the Fermi level of the emitter, $V_E$ the potential drop across a load impedance connected in series to the converter, $V_L$ and the potential drop to the necessary electrical connection to the collector, $V_C$. An expression for the maximum conversion efficiency has been developed. The expression yields optimum values of load impedance, collector lead geometry and emitter work function in terms of collector voltage, emitter temperature, effective emissivity of the emitter for both the theoretical and practically obtained Richardson- Dushman constant for a Pure Tungsten, $W$ metal surface. The results show that low value of collector voltage is required for a high efficiency; low radiation heat loss is required for a high conversion efficiency and relatively low values of emitter work function are required for maximum conversion efficiency at ordinary emitter temperature.

KEY WORDS: Thermionic converters, emitter, potential drop, Richardson-Dushman constant

INTRODUCTION

Since the early 1950s, there had been serious desires for lightweight, portable and quiet power supplies. This is also rooted in the interest in utilizing solar energy and realization of more electrical energy from atomic reactors. A lightweight electronic generator for space vehicles has also been sought for this long. Efforts have therefore been intensified to develop a means of generating electricity directly from heat, because it was observed that this would avoid the use of rotating machineries (Wilson, 1960).

Metals, as demonstrated by their ability to conduct electric current, contain mobile electrons. Most electrons in metals, particularly the “core” electrons close to the nucleus, are tightly bound to individual atoms. It is only the outermost valence electrons that are somewhat free. These free electrons are generally confined to the bulk of the metal. An electron trying to leave a conductor experiences a strong force attracting it back towards the conductor due to an image charge given as

$$F = -\frac{e^2}{4\pi\varepsilon_0(2y)^2}$$  \hspace{1cm} (1)

where $y$ is the distance of the electron from the interface and $e$ is the absolute value of the charge on an electron and $\varepsilon_0$ is the permittivity of free space. Of course, inside the metal, the electric field is zero so an electron there experiences zero (average) force. If we increase the temperature of the metal, the electrons will be moving faster and some will have enough energy to overcome the image-charge force (which after all becomes infinitesimally small at large distances from the interface) and then escape. This temperature induced electron flow is called thermionic emission (Houston, 1959; Baragiola and Bringa, 2006).

The process of converting thermal energy (heat) to a useful electrical work by the phenomenon of thermionic emission is the fundamental concept applied to a cylindrical version of the planner converter, considered as the building block for space nuclear power system (SNPS) at any power level. Space nuclear reactors based on this process can produce electrical power ranging from 5 kWh to 5 MWh. This spectrum serves the need of current users such as National Aeronautic and Space Administration (NASA) (Ramalingam and Young, 1993). Moreover, electrical power in this range is currently being considered for commercial telecommunications satellites, navigation, propulsion and planetary exploration mission to mention a few (Mysore, 1993).

The history of thermionic emission dates back to the mid 1700s when Chales Dufay observed that electricity is conducted in the space near a red-hot body. Although Thomas Edison requested a patent in the late 1800s indicating that he had observed thermionic emission while perfecting his electric light system, it was not until 1960s that the phenomenon of thermionic energy conversion was adequately described theoretically and experimentally (Gyftopoulos and Hatsopoulos, 1997).

Several attempts on the direct conversion of heat to electricity have been published (Houston, 1959; Rasor, 1960; Ingold, 1961; Xuan et al, 2003; Humphrey et al 2005). But all these employ the use of the theoretically assumed values of the Richardson-Dushman constant, $A$, in their analyses. However, it has been found experimentally that, $A$, varies from material to material (Culp, 1991). The emission properties of some typical materials used are presented in table 1 below.

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### Table 1: Thermionic emission properties of some materials
(Source: Culp 1991)

<table>
<thead>
<tr>
<th>Materials</th>
<th>$\phi$ (eV)</th>
<th>$A$ (A/m$^2$K$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cs</td>
<td>1.89</td>
<td>0.5x10$^6$</td>
</tr>
<tr>
<td>Mo</td>
<td>4.20</td>
<td>0.55x10$^6$</td>
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<tr>
<td>Ni</td>
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<tr>
<td>Pt</td>
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</tr>
<tr>
<td>Ta</td>
<td>4.19</td>
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<tr>
<td>W</td>
<td>4.52</td>
<td>0.6x10$^6$</td>
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<tr>
<td>W+Cs</td>
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<td>0.03x10$^6$</td>
</tr>
<tr>
<td>W+Ba</td>
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</tr>
<tr>
<td>W+Th</td>
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<td>0.04x10$^6$</td>
</tr>
<tr>
<td>BaO</td>
<td>1.50</td>
<td>0.001x10$^6$</td>
</tr>
<tr>
<td>SrO</td>
<td>2.20</td>
<td>1.00x10$^6$</td>
</tr>
</tbody>
</table>

The analyses in the existing work use both the practically obtained $A$ value (Culp 1991) and the theoretical value, for realistic results and hence the expected efficiency of the thermionic converters.

In the operation of the thermionic converter, electrons "boil-off" from the emitter material surface in a refractory metal such as tungsten, when heated to high temperatures (1600K-2000K). The electrons then traverse the small inter electrode gap, to a colder (800K-1000K) collector where they condense, producing an output voltage that drives the current through the electrical load and back to the emitter, (see Fig. 1). The flow of electrons through the electrical load is sustained by the temperature difference and the difference in surface work functions $\phi$ of the electrodes (Gyftopoulos, 1997).

![Fig. 1: Schematic diagram of an elementary thermionic converter](image-url)
METHODS AND THEORETICAL DEVELOPMENT

The converter output voltage

If we designate the work function of the emitter (cathode) as $\phi_E$ and that for the collector (anode) as $\phi_C$, then the total output voltage, $V_{out}$, is

$$V_{out} = \phi_E - \phi_C$$

where $V_{out}$ signifies the voltage across the load and the leads applied between the emitter and the collector.

![Potential diagram of a thermionic vacuum diode](image)

Fig. 2: Potential diagram of a thermionic vacuum diode

Note that as long as $V_{out} + \phi_C < \phi_E$, the barrier to electron flow is $\phi_E$ and the current is independent of the thermionic device voltage which is called saturation current, $j$, given by

$$j = AT^2_E \exp \left( - \frac{\phi_E}{k_B T_E} \right)$$

(3)

where, $T_E$ is the emitter temperature, $\phi_E$ is the emitter work function, $k_B$ is the Boltzmann constant and A is the Richardson-Dushman constant. However, when $V_{out} + \phi_C > \phi_E$, then the barrier is $V_{out} + \phi_C$ and any increase in $V_{out}$ will reduce $j$.

Figure 2 shows the potential diagram used in this work, where subscripts $E$ and $C$ denote emitter and collector respectively. And $\phi$ denotes work function, $V_E$ the potential difference. But the top of the potential barrier and the Fermi level of the emitter is seen to be equal to $\Delta V_E + \Delta V_L + \Delta V_I$, which is the voltage across the collector, load, and the leads. The net current density in the system is equal to $j_E - j_C$, which gets over the potential barrier. $j_E$ and $j_C$ are given by the Richardson-Dushman equation as

$$j_E = AT^2_E \exp \left[ - \frac{e \Delta V_E}{k_B T_E} \right]$$

(4)

and

$$j_C = AT^2_C \exp \left[ - \frac{e \Delta V_C}{k_B T_C} \right]$$

(5)

The effect of space charge

Once the electron cloud builds up between the electrodes, the flow of the electrons from the emitter is retarded by an additional potential, $\Delta V_{EB}$ (symbolising emitter barrier voltage). Adding in the voltage loss across the leads $\Delta V_L$ and the voltage loss across the load, $\Delta V_I$, as in Fig. 2 above gives

$$j_n = AT^2_E \exp \left[ - \frac{e (\Delta V_C + \Delta V_I + \Delta V_{CB})}{k_B T_E} \right]$$

(6)

where $V_{CB}$ is the collector barrier voltage, $V_{EB}$ is the emitter barrier voltage, $V_I$ is the lead voltage and $V_L$ is the load voltage.

Note that in Thermionics, large current requires small work function, and large $\Delta V_{EB}$ (i.e., $V_{out} \equiv \phi_E - \phi_C$) requires large work function.

Efficiency computation

Efficiency is defined as the useful electrical power output per unit area of the emitter divided by the power input per unit area of the emitter.
The useful electrical power output is given by \( (j_e - j_c) V_e \) = \( j V_e \). The case of practical interest, of course, is that for \( j_c \ll j_e \), otherwise there would be negligible power output from the device. This work would be restricted to the case for which \( j_c \) is very small compared to \( j_e \).

Consider equations (2) and (3), when \( j_c \ll j_e \) then

\[
\theta_c = \frac{d}{d \theta E}\exp\left( \frac{\Delta V_E}{\theta E} - \frac{\Delta V_C}{\theta C} \right) \approx 1
\]

where \( \theta = k_0 T/\epsilon \), and the subscript \( i \) could be emitter, \( E \), or collector, \( C \). For practical purposes therefore, the neglect of \( j_c \) in comparison with \( j_e \) in the following analysis is justified.

In the steady state, the heat input to the emitter is expected to be equal to the heat loss from the emitter.

\[
\text{Heat input} = \text{Heat output} \tag{9}
\]

The heat loss from the emitter consists of mainly three terms, which are as follows:

1. Electron emission cooling term, \( P_e \) (W/cm²)
   - This term is given by
   \[
P_e = j_e \left( \Delta V_E + \frac{2k_b T_E}{e} \right) \tag{11}
\]

2. Radiation heat losses, \( P_r \) (W/cm²) radiated from the hot emitter, and
3. Heat conduction and \( I^2R \) losses, \( P_l \) (W/cm²)
   - This term is given by
   \[
P_l = \sigma \left( T_E^4 - T_C^4 \right) \left( \frac{1}{\epsilon_E} + \frac{1}{\epsilon_C} \right) \left( \theta E - \theta C \right) \tag{13}
\]
   - where \( \epsilon_E \) is the emissivity of the emitter, \( \epsilon_C \) is the emissivity of the collector and \( \sigma \) is the Stefan-Boltzmann constant.

But from Fig.2,
\[
\Delta V_E = \Delta V_L + \Delta V_I + \Delta V_C \quad \text{and} \quad \Delta V_I = j_n A_e R_I.
\]

Therefore, we get
\[
P_e = j_n \left( \Delta V_L + j_n A_e R_I + \Delta V_C + \frac{2k_b T_E}{e} \right) \tag{12}
\]

There is another term in (12) which accounts for the energy received by the cathode from the electrons emitted from the anode which gets over the potential barrier. But for \( j_c \ll j_e \) this term is negligible.

(b) Radiation loss term, \( P_r \)
   - This term is given by
   \[
P_r = \sigma \left( T_E^4 - T_C^4 \right) \left( \frac{1}{\epsilon_E} + \frac{1}{\epsilon_C} \right) \left( \theta E - \theta C \right) \tag{13}
\]

(c) Heat conduction and thermal losses, \( P_l \)

i) Conduction loss, \( P_k \)
   - Heat loss due to conduction is given by
   \[
P_k = K_I A_I \left( T_E - T_L \right) \tag{14}
\]
   - where \( A_E \) is the surface area of the emitter, \( A_I \) is the cross-sectional area of the lead, \( K_I \) is the conductivity of the lead and \( l \) is the length of the lead.

   From the definition of resistivity, \( \rho \) the length of the lead, \( l \) is given by
   \[
l = \frac{R_A A_I}{\rho_I} \tag{15}
\]

Therefore, a useful expression for \( P_k \) is obtained as
\[
P_k = K_I A_I \left( T_E - T_L \right) \tag{16}
\]

However, from the Wideman – Franz law, one gets
\[
\rho K_I = \left( \frac{\pi^2}{6} \right) \left( \frac{k_b}{e} \right) \left( T_E + T_L \right),
\]

where \( T_L = \frac{T_E + T_L}{2} \), which leads to
\[
P_k = \left[ \frac{1}{A_E} \right] \left( \frac{\pi^2}{6} \right) \left( \frac{k_b}{e} \right)^2 \left( T_E^2 - T_L^2 \right) \tag{17}
\]

ii) Thermal Loss, \( P_j \) (Joule heating):
   - This is given by:
   \[
P_j = \left[ \frac{1}{A_E} \right] \left( j_n A_e \right)^2 R_I \tag{18}
\]

Assuming that half of the loss flows towards the cathode, then
\[ P_j = \frac{1}{2} \left[ \frac{1}{A_E} \right] (j_n A_E)^2 R_i \]  

(19)

The combined loss \((P_k + P_l)\)

The combined loss for the (i) and (ii) above is

\[ P = \frac{1}{4A_E} \sum \frac{\pi^2}{6A_E} \left( \frac{k_B}{e} \right)^2 \left[ (j_n^2 - T_E^2) - (j_n A_E)^2 R_i \right] \]

(20)

The efficiency of the diode, \(\eta\), is therefore

\[ \eta = \frac{P_L}{P_L + P_r + P_i} \times 100\% \]  

(21)

where \(P_L = j_n \Delta V_L\) (useful load/unit area of emitter).

Substituting the results for \(P_e, P_r,\) and \(P_i\) into (21) gives

\[ \eta = \frac{j_n \Delta V_L}{j_n \Delta V_L + j_n \Delta V_E + 2j_n \theta_E + P_r + P_i} \]  

(22)

where \(\theta_E = k_B T_e / e\) has been used. Dividing the numerator and the denominator of the right hand side of the above equation by \(j_n \theta_E\) and noting that \(V_i = j_n A_E R_i\) we can write the efficiency as

\[ \eta = \frac{\psi_L}{\psi_L + \psi_C + 2 + \left( \frac{P_r}{j_n \theta_E} \right) + \frac{\pi^2}{3} + \frac{1}{2} \psi_L} \]  

(23)

where \(\psi_L = V_i / \theta_E\). \(\beta / \theta_E^2\) has been neglected compared with \(\theta_E\) and \(j_n\) is given by

\[ j_n = j_a \exp (-\psi_C - e \psi_L - \psi_i) \]  

(24)

where \(j_a = A (e / k_B \beta) \theta_E^2\). According to (23) the efficiency can be interpreted as the ratio of power delivered to the load to the sum of powers delivered to the load and the anode (collector).

In optimizing \(\psi_L\) and \(\psi_i\) (i.e. \(V_i\) and \(V_L\)) it is convenient to work with the reciprocal of the efficiency, which from (23) is

\[ \frac{1}{\eta} = 1 + \frac{1}{\psi_L} \left[ \psi_C + 2 + \frac{P_r}{j_n \theta_E} + \frac{\pi^2}{3 \psi_L} + \frac{1}{2} \psi_L \right] \]  

(25)

where \(\psi_C, \theta_E\) and \(P_r\) are constant parameters. For \(\eta\) to be maximum (i.e. \(1/\eta\) to be minimum) it is required that

\[ \frac{\partial}{\partial \psi_L} \left[ \frac{1}{\eta} \right] = - \frac{P_r}{j_n \theta_E} + \frac{\pi^2}{3 \psi_L} + \frac{1}{2} = 0 \]  

(26)

and

\[ \frac{\partial}{\partial \psi_L} \left[ \frac{1}{\eta} \right] = \frac{1}{\psi_L} \frac{P_r}{j_n \theta_E} \frac{\partial}{\partial \psi_L} \left[ \frac{1}{\eta} \right] \]  

(27)

and from (24) one gets

\[ \frac{\partial}{\partial \psi_L} \left[ \frac{1}{\eta} \right] = -j_n \]

(28)

Therefore, from (26) and (27) one gets

\[ \psi_L = \pi \left( \frac{2}{3} \right)^{2/3} + 2 \left( \frac{P_r}{j_n \theta_E} \right) \]  

(29)

Equation (29) and (30) are not explicit solutions for the optimum values of \(\psi_L\) and \(\psi_C\) because \(j_n\) depends exponentially on these two parameters. Instead one has two equations, which must be solved simultaneously for the optimum values of \(\psi_L\) and \(\psi_C\). It turns out however, that first working with \(j_n\) alone can do this indirectly. Substituting equations (29) and (30) into (24) taking the logarithm of each side, and then simplifying gives

\[ \frac{P_r}{j_n \theta_E} + \frac{\pi^2}{3} + \frac{1}{2} \psi_L \]

(31)

where \(\beta = P_r / j_n \theta_E = e P_r / j_n k_B T_e\). Equation (31) is the condition on \(j_n\), hence on \(\psi_L\) and \(\psi_C\) for which \(\eta\) is a maximum.

Substituting (29) and (30) into (31) and simplifying the results gives maximum efficiency in terms of the optimum value of \(P_r / j_n \theta_E\) obtained from (31) as

\[ \eta_{max} = \frac{1}{1 + \left( \frac{P_r}{j_n \theta_E} \right)_{opt}} \]  

or

\[ \eta_{max} = \frac{1}{1 + \beta} \]  

(32)

Thus the maximum efficiency for particular values of \(V_i\) and \(T_E\) depends on the ratio of the radiation loss, \(P_r\), to the optimum value of \(2j_n \theta_E\), which is the kinetic energy, K.E. of the electrons that reach the anode (collector) from the cathode (emitter).

The optimum values of cathode lead resistance \(R_i\) and load impedance \(R_L\) can be obtained in terms of \(\beta\) from (29) and (30) by using the relation \(R_i = (\theta_E / j_n A_E) \psi_L\) as

\[ \left( R_i \right)_{opt} = \pi \left( \frac{2}{3} \right)^{2/3} \left( \frac{k_B T_e}{e} \right)^2 \frac{\beta}{e^2 P_r A_E (1 + 2 \beta)^{1/3}} \]  

(33)

and

\[ \left( R_L \right)_{opt} = \frac{1}{P_r A_E} \left[ \frac{k_B T_e}{e} \right]^{2/3} \frac{e A_L}{2 + \beta + \frac{2}{3} \left( 1 + \beta \right)^{1/3}} \]  

(34)

For the maximum efficiency, the following interrelated conditions must be satisfied.

(a) The current in the circuit must satisfy equation (31)

(b) The cathode or emitter lead resistance and the load impedance must satisfy equations (33) and (34) respectively.

(c) The optimum cathode lead geometry \(1 / A_E\) can be obtained directly from equation (20)

Data Generation

The data were generated by first solving equation (31) iteratively for different values of \(T_E\) and \(V_i\).
The results were used in connection with equation (32) to obtain the maximum conversion efficiency. Since to produce useful quantities of electricity the temperature of the collector has to be maintained in the same range as that of electron tube (i.e. 800 K to 1000 K), while the emitter is to be heated to about twice that temperature (i.e. 1500 to 2000 K), therefore, the emitter temperature, $T_E$ was varied from 1500 K to 5000 K in steps of 500 K and the collector voltage, $V_C$ was varied from 1.0 V to 3.0 V in steps of 0.5 V. This was done for the metal considered (Tungsten, W) with experimental Richardson-Dushman constant, $A = 55 \text{A/cm}^2\text{K}^2$ (Culp, 1991), as well as with the theoretical A value i.e. ($A = 120 \text{A/cm}^2\text{K}^2$). Tables of values were then computed based on both the theoretical and experimental values of $A$ (see Appendix).

**Fig. 3:** Conversion efficiency versus emitter temperature at different collector voltage, $V_C$ for Pure Tungsten using theoretical Richardson-Dushman constant, ($A = 120 \text{A/cm}^2\text{K}^2$)
Fig. 4: Conversion efficiency versus emitter temperature at different collector voltage, $V_C$, for Tungsten using experimental Richardson-Dushman constant, ($A = 60 \text{ A/cm}^2\text{K}^2$).

Fig. 5: Maximum conversion efficiency versus collector output voltage for both theoretical and experimental values of Richardson-Dushman, $A$ at $T_E = 5000\text{K}$.
ANALYSIS, RESULTS AND DISCUSSIONS

The graphs of maximum conversion efficiencies versus emitter temperatures were plotted for both theoretical and experimental Richardson-Dushman constant, A, for the various collector voltages. Also, a graph of maximum conversion efficiency against the output collector voltages was plotted using the values in tables 1 and 2 (see the Appendix). Analyses were drawn from both the tables and the graphs. From the tables it was observed that:-(1) The values for the efficiencies increase as the $\beta$ (as earlier defined) decreases. (2) The values of the efficiencies decrease along the row as the $V_C$ increases. (3) The values of the efficiencies increase along the column as the temperature increases. (4) There were no values for the efficiencies at $V_C = 2.5$ V and $V_C = 3.0$ V for $T_E = 1500$ K. This suggests that at this temperature and for these voltages the electrons do not have enough energy to cross the potential barrier for this metal surface. Therefore, for Tungsten no voltage is obtained if the emitter temperature does not exceed 1500 K.

From the graphs it was observed that:- (1) the curves for the efficiency become linear as the $V_C$ increases. (2) the curves for the theoretical A are higher than that for the experimental A. (3) From Fig. 5, the conversion efficiencies decrease linearly with the output collector voltages. (4) the constant difference between the theoretically obtained efficiency and the experimentally available efficiency for the metal considered is approximately 4% for all collector voltages $V_C$.

CONCLUSION

In summary, it is clear that variation in the Richardson-Dushman constant A affects the conversion efficiencies. In essence all the results of the thermionic conversion of heat to electricity obtained by assuming A to be 120 A/cm$^2$K$^2$ has this much deviation from the observed A value on a particular converter. To resolve this discrepancy, the following has to be considered (1) the effect of the reflection coefficient (2) the effect of the emitter work function (3) the surface ruggedness and (4) the effect of the external electric field all of which bring about the deviation of the Richardson-Dushman constant from its theoretical value.

REFERENCES


### APPENDIX

**Table 1:** Computed maximum conversion efficiency for Tungsten converter using theoretical A \((120 \text{A/cm}^2\text{K}^2)\) value.

<table>
<thead>
<tr>
<th>(T_E) (K)</th>
<th>(Pr) (W/m(^2))</th>
<th>(V_C = 1.0) (V)</th>
<th>(V_C = 1.5) (V)</th>
<th>(V_C = 2.0) (V)</th>
<th>(V_C = 2.5) (V)</th>
<th>(V_C = 3.0) (V)</th>
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<tr>
<td></td>
<td>(\beta)</td>
<td>(\eta)%</td>
<td>(\beta)</td>
<td>(\eta)%</td>
<td>(\beta)</td>
<td>(\eta)%</td>
</tr>
<tr>
<td>1500</td>
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<td>56.31</td>
<td>0.9980</td>
<td>50.05</td>
<td>1.2710</td>
</tr>
</tbody>
</table>

**Table 2:** Computed maximum conversion efficiency for Tungsten converter using experimental A \((60 \text{A/cm}^2\text{K}^2)\) value.

<table>
<thead>
<tr>
<th>(T_E) (K)</th>
<th>(Pr) (W/m(^2))</th>
<th>(V_C = 1.0) (V)</th>
<th>(V_C = 1.5) (V)</th>
<th>(V_C = 2.0) (V)</th>
<th>(V_C = 2.5) (V)</th>
<th>(V_C = 3.0) (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(\beta)</td>
<td>(\eta)%</td>
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<td>(\eta)%</td>
<td>(\beta)</td>
<td>(\eta)%</td>
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