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# Continued convection and the initial recovery of *Dst*

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[1] We test the hypothesis that abrupt cessation of solar wind driving results in a different recovery profile for *Dst* than does a slow cessation. The difference arises when abrupt cessation of convection causes a large portion of the asymmetric ring current to be trapped, whereas continued, weakened convection permits a rapid initial loss of ring current particles through the dayside magnetopause. Specifically, we compare the initial recovery of the hourly *Dst* index for storms with gradual versus abrupt northward turning of the interplanetary magnetic field (IMF). We consider only storms with minimum *Dst* between $-150$ nT and $-300$ nT. We show that storms with abrupt northward turnings show the same recovery in the first 6 hours or slightly more recovery than do the storms with gradual northward turnings. Our results contradict the hypothesis that the rate of northward turning (i.e., shutoff of convection) largely determines the initial rate of recovery in *Dst*. *INDEX TERMS:* 2778 Magnetospheric Physics: Ring current; 2784 Magnetospheric Physics: Solar wind/magnetosphere interactions; 2760 Magnetospheric Physics: Plasma convection; 2730 Magnetospheric Physics: Magnetosphere—inner; 2708 Magnetospheric Physics: Current systems (2409). **Citation:** O'Brien, T. P., R. L. McPherron, M. W. Liemohn, Continued convection and the initial recovery of *Dst*, *Geophys. Res. Lett.*, *29*(23), 2143, doi:10.1029/2002GL015556, 2002.

## 1. Introduction

[2] Recent simulation work has made great strides toward understanding the details of ring current evolution during magnetic storms. *Takahashi et al.* [1990] showed that the flow-through of ions out the dayside magnetopause can be a significant loss mechanism for the stormtime ring current. While numerous subsequent studies have examined the recovery-phase decay of the ring current [e.g., *Chen et al.*, 1993, 1994; *Fok et al.*, 1993, 1996; *Jordanova et al.*, 1994, 1996; *Noel*, 1997; *Kozyra et al.*, 1998a, 1998b] few of these studies emphasized the possibility of the "flow-out" effect significantly contributing to the loss of hot ions in the inner magnetosphere. A quantitative assessment of the relative importance of flow-out losses was finally conducted by *Liemohn et al.* [1999], concluding that this process can be the dominant ring current decay term during the early part of the recovery phase.

[3] It was then hypothesized that when the *Dst* index reaches its minimum during a magnetic storm, most of the energy in the ring current resides in particles that will not complete a full drift orbit before being lost through the magnetopause [*Liemohn et al.*, 2001a]. Accordingly, during the initial recovery of a magnetic storm, the asymmetric main phase ring current is converted to a symmetric ring current as some of these particles are trapped on closed drift orbits. The rate of trapping and conversion to symmetric ring current is controlled by the rate of northward turning of the interplanetary magnetic field (IMF). If the IMF turns northward slowly, presumably much of the energetic plasma of the asymmetric ring current will be lost through the magnetopause according to the "flow-out" effect [*Takahashi et al.*, 1990]. If the IMF turns northward quickly, much of the energetic plasma will be trapped as a symmetric ring current [*Liemohn et al.*, 2001a]. In addition to the rate of northward turning of the IMF, *Liemohn et al.* [2001a] identify the near-earth plasma sheet density as playing an important role in determining the efficacy of the flow-out effect.

[4] While all of the implications are not yet completely clear, the preceding body of work leads us to examine the initial *Dst* recovery associated with abrupt as opposed to gradual northward turnings in the IMF. We show below that the IMF effects are not obvious in a sample of 30 large magnetic storms. Note that we are only considering this one factor with respect to *Dst* recovery. Other factors, such as plasma sheet temperature [*Ebihara and Ejiri*, 2000] and composition [*Hamilton et al.*, 1988; *Kozyra et al.*, 1998a], also contribute to the dynamics of the stormtime ring current. For a complete review, see *Daglis* [1997] and *Daglis et al.* [1999].

## 2. Storm Selection and Analysis

[5] We select large magnetic storms as having minimum *Dst* between $-300$ nT and $-150$ nT (inclusive). We identify 79 storms in the interval from November 1963 through September 2001. Using the Omni database of interplanetary conditions, we have solar wind velocity and IMF data for at least 4 of the first 6 hours after *Dst* minimum in only 29 of the 79 storms. We break these 29 storms into two categories based on the average of *VBs* for the first 6 hours after minimum *Dst*. We define hourly *VBs* as the product $VB_z$ of hourly solar wind velocity and IMF parameters in GSM coordinates, where we rectify the product to be positive when $B_z$ is southward and zero when $B_z$ is northward. We designate as "fast" shutoff the 13 storms with 6-hour

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**Table 1.** Magnetic Storms Included in Study

| Date | *Dst* (nT) | | *VBs*[a](mV m$^{-1}$) | |
|---|---|---|---|---|
| | min | +6 h | main | recovery |
| Fast Shutoff Storms | | | | |
| 08-Mar-1970 | −284 | −193 | 7.5 | 0.6 |
| 01-Apr-1973 | −211 | −138 | 8.8 | 1.2 |
| 18-Sep-1979 | −158 | −86 | 4.4 | 0.0 |
| 20-Oct-1981 | −192 | −136 | 4.9 | 0.7 |
| 12-Sep-1986 | −170 | −121 | – | 0.6 |
| 30-Mar-1990 | −187 | −111 | – | 0.0 |
| 13-Jun-1990 | −150 | −90 | – | 0.3 |
| 29-Oct-1991 | −254 | −155 | – | 1.1 |
| 21-Feb-1992 | −171 | −112 | 8.0 | 1.9 |
| 04-May-1998 | −205 | −136 | 10.7 | 0.9 |
| 22-Sep-1999 | −173 | −128 | 4.7 | 1.1 |
| 22-Oct-1999 | −237 | −166 | 10.6 | 0.7 |
| 12-Feb-2000 | −169 | −132 | 4.3 | 1.8 |
| Slow Shutoff Storms | | | | |
| 14-Jan-1967 | −160 | −119 | 6.2 | 2.3 |
| 02-Feb-1969 | −186 | −136 | 7.3 | 3.2 |
| 24-Mar-1969 | −228 | −194 | 6.8 | 4.0 |
| 06-Jul-1974 | −204 | −145 | 5.3 | 3.6 |
| 10-Jan-1976 | −156 | −88 | 6.9 | 2.3 |
| 28-Aug-1978 | −226 | −152 | 8.2 | 5.0 |
| 29-Sep-1978 | −224 | −195 | 12.5 | 11.3 |
| 19-Dec-1980 | −240 | −171 | 14.2 | 3.2 |
| 25-Jul-1981 | −226 | −197 | 8.3 | 8.4 |
| 02-Mar-1982 | −211 | −180 | 9.4 | 6.5 |
| 06-May-1988 | −160 | −129 | 4.9 | 5.3 |
| 09-Jul-1991 | −194 | −143 | 11.4 | 4.5 |
| 27-Aug-1998 | −155 | −138 | 6.8 | 7.2 |
| 25-Sep-1998 | −207 | −121 | 9.1 | 6.3 |
| 20-Mar-2001 | −165 | −136 | 6.9 | 4.7 |
| 11-Apr-2001 | −256 | −154 | 8.5 | 4.3 |

[a]6-hour averages either side of minimum *Dst*.

average *VBs* of less than 2 mV m$^{-1}$, and the other 16 we designate as "slow" shutoff. It should be noted that *VBs* is only a proxy for the magnetospheric electric field. We summarize the basic features of each storm in Table 1, including minimum *Dst*, *Dst* 6 hours later, and average of *VBs* in the 6 hours ending at and following minimum *Dst*.

[6] A superposed epoch depiction of the hourly evolution of *Dst* and interplanetary parameters is given in Figure 1. At each epoch time, for each quantity depicted, we compute the upper and lower quartiles and the median value for each category, where each storm contributes one point to the sample distribution in its respective category. It is clear from panels (a) and (b) that the classification criteria correctly distinguish between storms with fast as opposed to slow shutoff of convection (or rapid as opposed to gradual northward turning of the IMF). Panel (c) shows that the two categories have similar distributions of solar wind density, with the fast shutoff storms having slightly higher density. Panel (d) shows that the first 6 hours of the recovery phase is actually quite similar in both sets of storms. This similarity is in contrast to claims that the timescale of recovery in *VBs* largely determines the timescale of initial recovery in *Dst* [e.g., *Liemohn et al.*, 2001a]. To quantify this result, we should examine the superposed epoch distributions more closely.

[7] Before we can quantitatively examine the recovery of the storms in our two categories, we must verify that the two categories start out with similar initial (minimum) *Dst* distributions. Figure 2 shows that the two categories of storms have essentially identical distributions of minimum

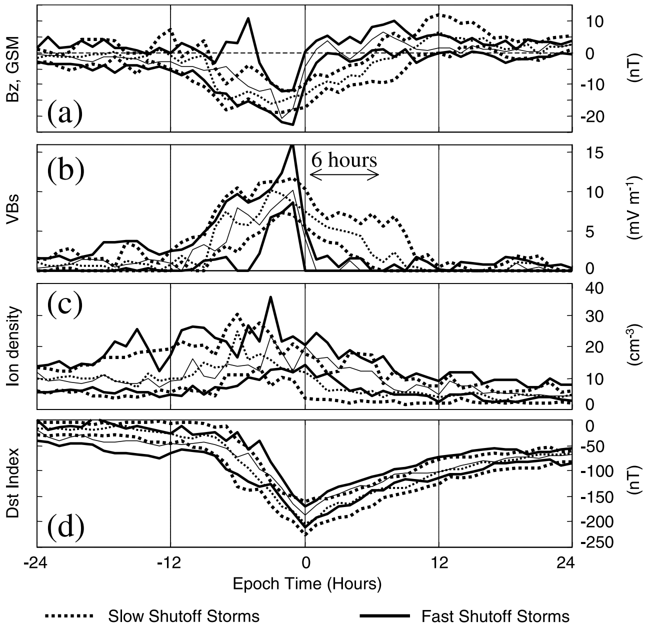


**Figure 1.** A superposed epoch representation of fast and slow shutoff magnetic storms. Epoch time zero is defined as minimum *Dst*. The heavier solid and dashed lines indicate upper and lower quartiles, while the thinner solid and dashed lines indicate medians.

*Dst*. The figure depicts the cumulative distribution, which is a sort of integrated histogram. The statistic Δ measures the maximum vertical separation between the two cumulative distributions. According to the Kolmogorov-Smirnov test of significance [*Press et al.*, 1992], there is an 81% chance of measuring a Δ of 23% or larger for two samples of 13 and 16 points taken from the same population. That is, the two

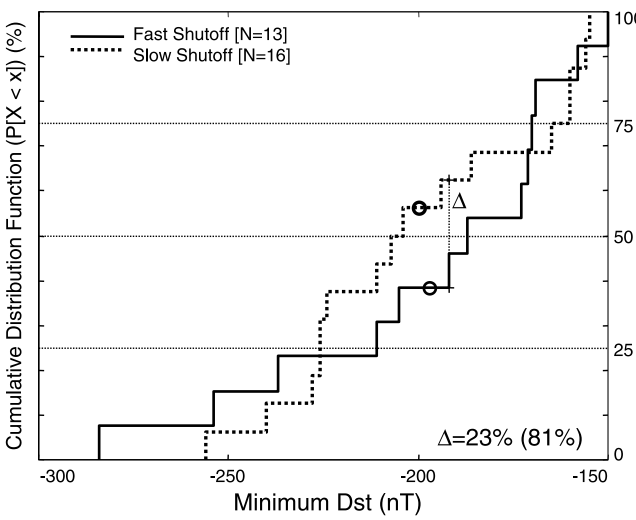


**Figure 2.** Cumulative distributions of minimum *Dst* in fast and slow shutoff storms. The heavy solid and dashed lines indicate the fraction of samples in each distribution that is less than the value along the abscissa. Circles indicate the mean value of each distribution. The number given in parentheses is the likelihood of measuring Δ for two samples from the same parent distribution.

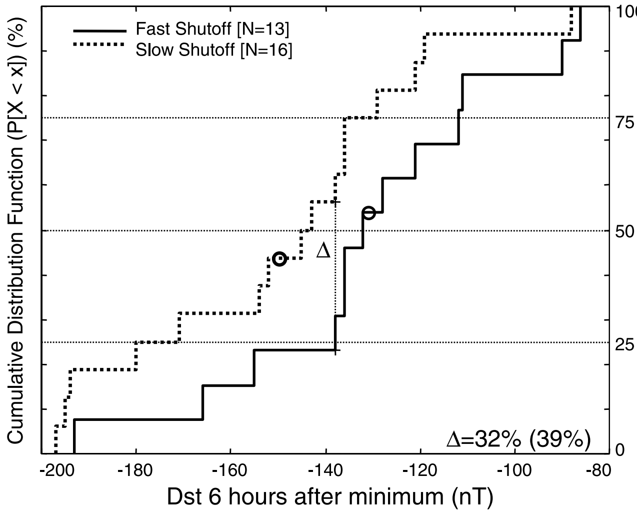


**Figure 3.** Cumulative distributions of *Dst* 6 hours after minimum in fast and slow shutoff storms. In the format of Figure 2.

categories of storms have statistically indistinguishable distributions of minimum *Dst*.

[8] Because our two categories of storms differ greatly in their upstream solar wind conditions over the first 6 hours of the recovery phase, we expect them to show markedly different behavior in the recovery of *Dst*. Specifically, we expect the distribution of *Dst* after 6 hours of recovery to be quite different in the two categories. Figure 3 compares these distributions in the same format as Figure 2. After 6 hours of recovery under quite different IMF conditions, the two sets of storms show only a slight change in their relative distributions. Namely, the test statistic $\Delta$ is now 32%, which occurs 39% of the time when taking samples of 13 and 16 points from the same parent distribution. That is, the two distributions are not significantly different from each other.

[9] Quantitatively, over the first 6 hours of recovery the mean *Dst* changed from $-197 \pm 11$ nT to $-131 \pm 8$ nT for the fast shutoff storms, whereas mean *Dst* recovered from $-200 \pm 8$ nT to $-150 \pm 8$ nT in the slow shutoff storms. Using a *t*-test for means, there is an 11% chance that these final *Dst* values are the same (which is not significant at the usual 5% upper limit). If these final *Dst* values were significantly different from each other, the fast shutoff storms produce slightly greater decrease in *Dst* ($\sim$65 nT) compared to the slow shutoff storms ($\sim$50 nT).

[10] The average of *VBs* over the 6 hours is $0.8 \pm 0.2$ mV m$^{-1}$ for the fast shutoff storms, whereas it is $5.1 \pm 0.6$ mV m$^{-1}$ in the slow shutoff storms. Recall that we define $VBs = 0$ for $B_z > 0$, which inflates these 6-hour averages. According to empirical models such as that of *O'Brien and McPherron* [2000] (hereafter OM2K), injection is given by $Q = (-4.4 \text{ nT h}^{-1})(VBs - 0.49 \text{ mV m}^{-1})$. Continued injection in the slow shutoff storms could easily account for their relatively lower final *Dst* and hence weaker recovery. Even though the model was developed for more modest storms, we use the OM2K formula to model the first 6 hours of recovery for the 19 storms with full solar wind data coverage. Of these, 7 were fast shutoff storms, and 12 were slow shutoff storms. Figure 4 shows that the OM2K error after 6 hours of modeling from minimum *Dst*, does not show a systematic trend with the average *VBs*. Quantitatively, the rank order correlation coefficient between the errors and the average of *VBs* is $0.1 \pm 0.2$, not significantly different from zero. Also, using the Kolmogorov-Smirnov test, the distributions of errors in the two storm categories are statistically identical. It should be noted that the errors (model *Dst* - true *Dst*) tend to be negative, indicating that the OM2K model does not capture the rapid initial recovery of *Dst* in these large storms. *Liemohn et al.* [2002] have shown that the OM2K loss lifetimes are likely a combination of charge exchange and flow-out effects. The predominantly negative errors signify that either (1) the OM2K loss lifetime is temporarily too large, as is likely during the fast shut-off recoveries, or (2) the injection is too large, as is likely the case during the slow-shut-off recoveries.

[11] It should be noted that in the OM2K model runs the slow shutoff storms show about $\sim$90 nT of extra injection during the recovery phase, which is masked by $\sim$90 nT of faster recovery (in OM2K the recovery time scale is shorter for larger *VBs*). Therefore, the similarity in *Dst* recovery profiles may be hiding a dramatically different magnetospheric behavior in the two categories of storms. Nonetheless, given the similarity in recovery profiles and the similarity in errors from the OM2K model, there is no clear evidence that the rapid initial recovery of *Dst* is a result primarily of the electric field in the solar wind. While fast versus slow shutoff of *VBs* cannot be used as an indicator of how *Dst* will recover, if they are to be believed, these OM2K modeling results indicate that the loss processes must be vastly different to account for the similarity in *Dst* evolution. The most logical explanation is that flow-out provides the additional loss, being equal to or greater than charge-exchange loss during slow-shutoff-storm recovery.

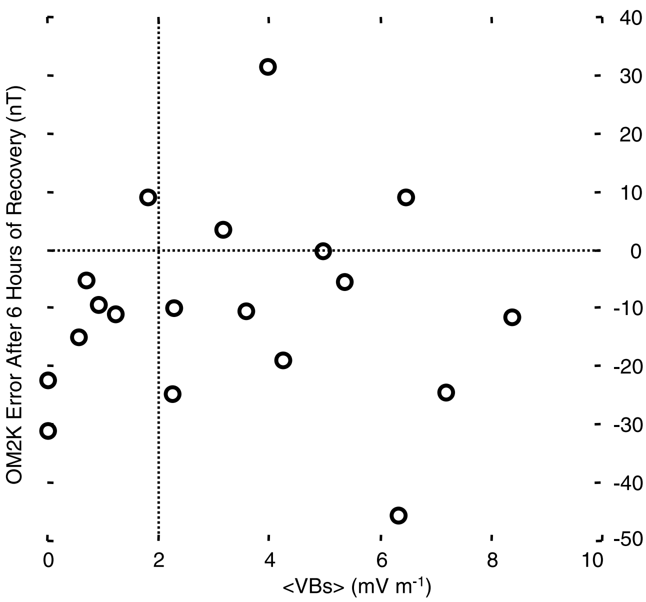


**Figure 4.** Errors (model *Dst* - true *Dst*) in the OM2K model after the first 6 hours of recovery is uncorrelated with the average of *VBs* during the 6-hour interval. The vertical line at 2 mV m$^{-1}$ indicates the division between fast shutoff and slow shutoff storms.

## 3. Conclusions

[12] We have shown that the initial recovery of *Dst* in 30 large storms is not strongly dependent on whether the IMF turns sharply northward or remains southward during the initial recovery. The final values of *Dst* after the first 6 hours of recovery show slightly more recovery in the cases of sharp northward turning. This difference is not statistically significant for our samples. We conclude that the recovery mechanism responsible for fast initial recovery of *Dst* is not closely related to the rate of northward turning, represented by the rate of recovery in *VBs*.

[13] The "flow-out" effect described by previous authors [*Takahashi et al.*, 1990; *Liemohn et al.*, 1999, 2001a, 2001b], is the best candidate for the rapid initial recovery of *Dst*. This loss process theoretically depends on the strength of the convection electric field and the inner plasma sheet density. We have shown that *VBs*, a proxy for the strength of the convection electric field, does not control the fast initial recovery of *Dst*. Rather, widely different signatures in recovery phase *VBs* give very similar initial responses in *Dst*. Therefore, we conclude that the net result of the flow-out effect, or whatever causes the rapid initial recovery of *Dst*, may be more closely associated with the near-earth plasma sheet density than with the recovery of the convection electric field. Notably, our study does not rule out the possibility that the main phase convection electric field modifies the plasma sheet density, and thereby convection still plays a role in determining the initial recovery of *Dst*.

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## References

Chen, M. W., M. Schulz, L. R. Lyons, and D. J. Gorney, Stormtime transport of ring current and radiation belt ions, *J. Geophys. Res.*, *98*, 3835–3849, 1993.

Chen, M. W., L. R. Lyons, and M. Schulz, Simulations of phase space distributions of storm-time proton ring current, *J. Geophys. Res.*, *99*, 5745–5759, 1994.

Daglis, I. A., The role of magnetosphere-ionosphere coupling in magnetic storm dynamics, in *Magnetic Storms, Geophys. Monogr. Ser.*, vol. 98, edited by B. T. Tsurutani, W. D. Gonzalez, Y. Kamide, and J. K. Arballo, pp. 107–116, AGU, Washington, DC, 1997.

Daglis, I. A., R. M. Thorne, W. Baumjohann, and S. Orsini, The terrestrial ring current: origin, formation, and decay, *Rev. Geophys.*, *37*, 407–438, 1999.

Ebihara, Y., and M. Ejiri, Simulation study on fundamental properties of the storm-time ring current, *J. Geophys. Res.*, *105*, 15,843–15,860, 2000.

Fok, M.-C., J. U. Kozyra, A. F. Nagy, C. E. Rasmussen, and G. V. Khazanov, Decay of equatorial ring current ions and associated aeronomical consequences, *J. Geophys. Res.*, *98*, 19,381–19,393, 1993.

Fok, M.-C., T. E. Moore, and M. E. Greenspan, Ring current development during storm main phase, *J. Geophys. Res.*, *101*, 15,311–15,322, 1996.

Hamilton, D. C., G. Gloeckler, F. M. Ipavich, W. Studemann, B. Wilkey, and G. Kremser, Ring current development during the great geomagnetic storm of February 1986, *J. Geophys. Res.*, *93*, 14,343–14,355, 1988.

Jordanova, V. K., J. U. Kozyra, G. V. Khazanov, A. F. Nagy, C. E. Rasmussen, and M.-C. Fok, A bounce-averaged kinetic model of the ring current ion population, *Geophys. Res. Lett.*, *21*, 2785–2788, 1994.

Jordanova, V. K., L. M. Kistler, J. U. Kozyra, G. V. Khazanov, and A. F. Nagy, Collisional losses of ring current ions, *J. Geophys. Res.*, *101*, 111–126, 1996.

Kozyra, J. U., M.-C. Fok, E. R. Sanchez, D. S. Evans, D. C. Hamilton, and A. F. Nagy, The role of precipitation losses in producing the rapid early recovery phase of the Great Magnetic Storm of February 1986, *J. Geophys. Res.*, *103*, 6801–6814, 1998a.

Kozyra, J. U., V. K. Jordanova, J. E. Borovsky, M. F. Thomsen, D. J. Knipp, D. S. Evans, D. J. McComas, and T. E. Cayton, Effects of a high-density plasma sheet on ring current development during the November 2–6, 1993, magnetic storm, *J. Geophys. Res.*, *103*, 26,285–26,306, 1998b.

Liemohn, M. W., J. U. Kozyra, V. K. Jordanova, G. V. Khazanov, and M. F. Thomsen, Analysis of early phase ring current recovery mechanisms during geomagnetic storms, *Geophys. Res. Lett.*, *26*(18), 2845–2848, 1999.

Liemohn, M. W., J. U. Kozyra, M. F. Thomsen, J. L. Roeder, G. Lu, J. E. Borovsky, and T. E. Cayton, Dominant role of the asymmetric ring current in producing the stormtime *Dst**, *J. Geophys. Res.*, *106*, 10,883–10,904, 2001a.

Liemohn, M. W., J. U. Kozyra, C. R. Clauer, and A. J. Ridley, Computational analysis of the near-Earth magnetospheric current system during two-phase decay storms, *J. Geophys. Res.*, *106*, 29,531–29,542, 2001b.

Liemohn, M. W., J. U. Kozyra, C. R. Clauer, G. V. Khazanov, and M. F. Thomsen, Adiabatic energization in the ring current and its relation to other source and loss terms, *J. Geophys. Res.*, *107*, April 1 2002.

Noel, S., Decay of the magnetospheric ring current: A Monte Carlo simulation, *J. Geophys. Res.*, *102*, 2301–2308, 1997.

O'Brien, T. P., and R. L. McPherron, An empirical phase space analysis of ring current dynamics: Solar wind control of injection and decay, *J. Geophys. Res.*, *105*, 7707–7720, 2000.

Press, W. H., S. A. Teukolsky, W. T. Vettering, and B. P. Flannery, *Numerical Recipes in C*, Cambridge Univ. Press, New York, 1992.

Takahashi, S., T. Iyemori, and M. Takeda, A simulation of the storm-time ring current, *Planet. Space Sci.*, *38*, 1133, 1990.

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