A NOVEL TRANSDUCER FOR MONITORING SURGE CURRENTS IN AC MAINS: Expectations and Reality

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Significance
Part 5 – Monitoring instruments, laboratory measurements, and test methods
Part 6 – Textbooks and tutorial reviews

The paper is a follow-up on earlier proposals to establish a program for characterizing surge events according to the capability of a surge event to deliver a surge current through the power distribution system in end-user facilities. This characterization would replace the conventional and by now misleading monitoring of surge voltages. The new approach uses a current transducer including a silicon-avalanche diode with the lowest possible voltage to "attract" surges away from other surge-protective devices connected within the facility. Tests performed in a replica of a residential power distribution system indicate that the transducer would be effective if connected at the service entrance, but that if installed further into the branch circuits, competing MOVs that are most likely to be present would deprive the transducer from recording the full surge current.

This subject was addressed in several other papers (See in Part 5 "Keeping up" 1995; "No joules" 1996; "Make sense" 1996; Joules Yes-No" 1997; and "Galore," 1999 in Part 2) in persistent but unsuccessful attempts to persuade manufacturers and users of power quality monitors to address the fallacy of continuing to monitor surge voltages in post-1980 power distribution systems. As it turned out, the response was polite interest but no action.

A NOVEL TRANSDUCER FOR MONITORING SURGE CURRENTS IN AC MAINS: Expectations and Reality

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Abstract — The proliferation of surge-protective devices and switch-mode power supplies has radically changed the surge environment in the low-voltage AC mains. Monitoring surge voltages has lost significance and can be misleading. Instead, surge currents should be monitored. The paper describes the performance of a silicon-based surge-protective device acting as a "magnet" for impinging surges in the presence of multiple metal-oxide varistors. This "magnet" is the first step toward the development of a transducer producing a voltage signal reflecting the surge current that can be delivered by the power system. That signal can then be applied to the voltage input of existing power quality monitors.

I. BACKGROUND

The need to shift focus from voltage surge monitoring to current surge monitoring was presented at the EMC1996 Roma Symposium [1]. The need for this change of focus is the proliferation of surge-protective devices (SPDs) to the point that monitoring voltage surges only shows what these SPDs allow, not the real surge activity [2]. The proposed approach was to use a transducer to deliver a voltage signal suitable for the high-frequency response channels of commercial power quality monitors. Most existing monitors equipped with current input channels are designed for monitoring low-frequency harmonics; these inputs are not suitable for recording surge currents.

This voltage signal would represent the maximum surge current that the power system can deliver at any point of the system, by offering to any impinging surge the most attractive path to earth — that is, the lowest impedance — thanks to a highly nonlinear characteristic. Hence, the terms "magnet" or "low bidder" used in this paper to characterize the function of the transducer.

The initial 1996 proposal placed emphasis on developing a simple, low-cost adapter, even though the result would only be an approximation of the true current waveform (the peak amplitude would be calibrated). In the state of affairs prevailing at that time, and still at present, it was felt that an imperfect approximation would still be an improvement over the complete lack of information on possible surge currents.

Figure 1, reproduced from the 1996 paper [1], shows the difference between the response of the low-cost system versus a laboratory-grade current-viewing transducer. For the measurements reported in the present paper, the issue of low cost vs. laboratory precision was set aside to concentrate on assessment of the "magnet" performance.

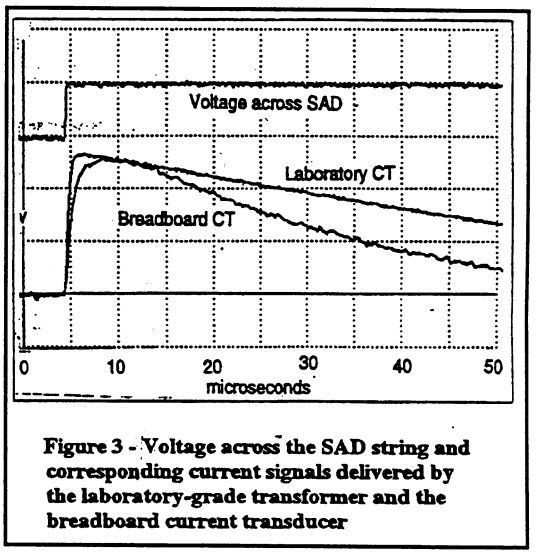

Figure 1 — Performance of the 1996 breadboard

One of the limitations acknowledged in the 1996 proposal was the risk of failure for the low-cost "magnet" in case of very large surges or temporary overvoltages. To address that concern, a new set of measurements was undertaken with a silicon-avalanche diode (SAD) device that has been successfully deployed in the field as a commercial SPD, demonstrating its survival capability.

A new urgency for this shift of focus has emerged as the International Electrotechnical Commission (IEC) has recently undertaken the development of a new standard for measurements of power quality parameters [3]. If the feasibility of recording current surges rather than, or in addition to, voltage surges can be demonstrated in time, the IEC standard might include such a shift of focus in its recommendations.

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This paper reports tests performed to assess the viability of the "low bidder" function, and the implications for a successful deployment of the transducer in the presence of competing metal-oxide varistors (MOVs) such as those used in the many plug-in packaged surge suppressors found in today's installations. Hopefully, these test results will help arouse interest among would-be users and manufacturers for developing a complete package, an activity which is not in the scope of the authors' charter. These tests included:

1. Evaluating the effects of separation distance between competing MOVs and the SAD in a simple multi-branch circuit.
2. Identifying the relationship between the SAD and MOVs likely to be found in a facility, when connected directly in parallel.
3. Investigating the behavior of the SAD in the face of likely sustained power-frequency overvoltages.

II. COMPETITION WITH OTHER SPDs

The terms "magnet" and "low bidder" are used in this discussion to emphasize the present situation in end-user installations where a proliferation of SPDs has occurred. These SPDs are essentially highly nonlinear devices and offer a low-impedance path toward earth for the flow of surge currents. Effectively connected in parallel, they act as "bidders" to the surge source, and the one with the lowest impedance becomes the winner of the competition — so goes it in theory.

The reality is not quite so simple. Two major, different SPD applications have developed in parallel: SADs and MOVs. Ever since their competing introduction in the seventies, the perception has prevailed that SADs exhibit a sharper knee in their V-I characteristic, compared to that of MOVs. Thus, if placed directly in parallel, the SAD would be expected to act more aggressively than the many MOVs in capturing the largest part, if not all, of an impinging surge.

The literature reports many tests and simulations of what is called "cascade coordination" [4], [5], [6], [7], [8], a situation where the two "competing" SPDs are separated by some inductance, in contrast with the direct parallel connection, the subject of the second test cited in (2) above. The effect of this inductance is that an SPD with a dynamic impedance slightly higher than that of its competitor can still take on most of the current if the competitor is located downstream along the surge path, because the voltage drop caused by the inductance is added to the clamping voltage of the SPD.

However, competition for offering the lowest dynamic impedance has the undesirable side effect of lowering the voltage beyond which a temporary overvoltage could severely overstress the SPDs [9].

Manufacturers publish MOV specifications that include a min-max range of the nominal voltage at the 1 mA DC level [10], [11]. For instance, 20 mm discs rated 130 V rms — a popular choice for many packaged SPDs in 120 V AC applications — have a nominal voltage of 200 V, with a minimum of 184 V and maximum of 228 V or 220 V. Therefore, the strongest competition would come from those devices on the low side of the tolerance range for the nominal voltage.

To obtain some feel of the actual range — not a universal statement — a lot of one hundred 130-V MOVs was purchased directly from a distributor, presumably coming from the same manufacturing lot. The nominal voltage at 1 mA DC was measured for all 100 devices. Only three devices were at or below 190 V, only four at or above 207 V, and the median was 198 V. Therefore, a typical competition for the SAD would be with a 198-V varistor. An unfavorable handicap for the SAD would be to compete with a varistor with nominal voltage of 190 V or below, and an easy win would be for the upper half, say at 205 V. Devices with these three levels of nominal voltage were selected from the one-hundred lot to perform the coordination tests described in the following section.

III. CASCADE OPERATION

The test circuit shown schematically in Figure 2 was configured with conventional non-metallic jacket cable of three conductors, #12 AWG (2.05 mm diameter). Three lengths of cable were provided: 3 m, 10 m, and 30 m, all connected in parallel at a common point (as they would be in the service panel of an actual installation). A surge generator capable of delivering a 6 kA 8/20 μs current was used to inject the surge at this common point. A fixed setting of 3 kA available short circuit current was maintained for all tests.

Four current-viewing transducers were installed in the circuit, to record the currents identified as I_0, I_3, I_{10}, and I_{30} in Figure 2. The output signals were fed to a digital signal analyzer capable of displaying the waveforms and performing the computations for direct reading of the peak values of the currents.

Figure 3 is a typical oscillogram, with all the complex numerical data of the display edited out. The scale factors of the oscillograms were adjusted to obtain visible deflections, with the peak values read from the display transcribed on the right of the oscillogram The complete set of results of the coordination measurements† are summarized in Table 1 and Table 2.

† *The measurements reported in this paper have been made with instruments and transducers with cumulative relative uncertainty that should not exceed 5% to 6%. Given the goal of applying these results to monitoring highly scattered values of current surges, as they occur in the field, the conclusions are not affected by this level of uncertainty.*

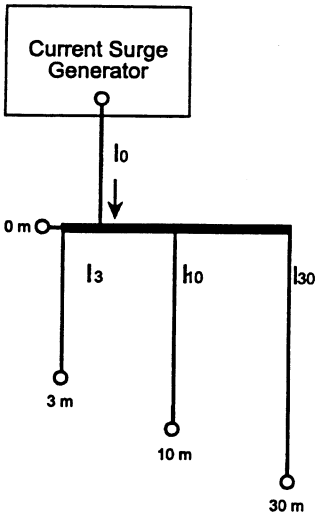


Figure 2 — Test circuit for cascade coordination

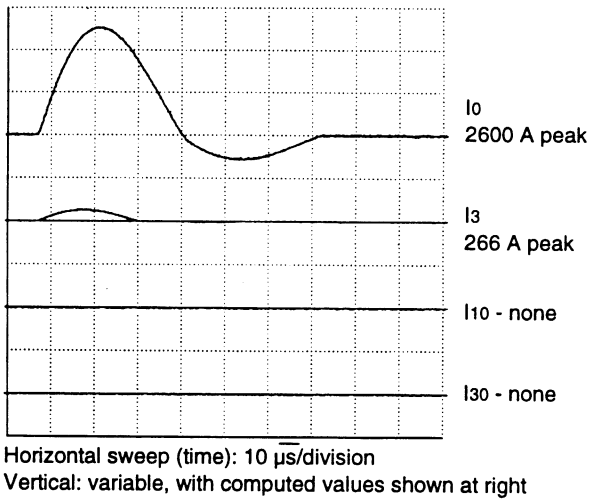


Figure 3
Current sharing between SAD located at 0 m and single 198-V MOV located at 3 m, 3 kA 8/20 available current

III-a — Tests with SAD at the panel bus

Table 1 shows the results of the first test series where the SAD was connected at the panel bus, the point identified as 0 m in Figure 2.

Table 1
Current sharing between SAD connected at point 0 m and one or more MOVs connected at points 3 m, 10 m, and 30 m with a 3 kA setting for the available current

Varistor nominal voltage (V)	Point(s) of connection of MOVs	Percent of impinging current captured by MOVs †
190	3 m only	11.1
	10 m only	3.9
	30 m only	2.2
	All 3 m, 10 m, 30 m	15.2
198	3 m only	10.2
	10 m only	3.6
	30 m only	2.2
	All 3 m, 10 m, 30 m	14.5
205	3 m only	10.1
	10 m only	3.6
	30 m only	2.0
	All 3 m, 10 m, 30 m	13.6

† The three single-MOV values do not add to the value for all three MOV being connected, because of the interactions in sharing the total current.

Three sets of measurements were performed with the three levels of MOV nominal voltage, as discussed above. In each set, first only one varistor was connected at the end of a branch circuit, then all three branch circuits were equipped with a varistor. The impinging surge was obtained from the generator at a constant setting of 3 kA available short-circuit current. With the SAD taking most of the current, the actual impinging surge was not much affected by the small variations in the currents drawn through the MOVs, and was in the range of 2500 A to 2600 A.

Inspection of the table shows that over the range of MOV nominal voltages, there are relatively small changes in the currents being diverted away from the "magnet" SAD. With three MOVs, the error in accepting the SAD current as representing the system delivery capability would be about 15%. Given the present lack of knowledge on the possible current surges, and the certain wide scattering of their amplitudes, a 15% error in reporting values is a small price to pay for new information on SPD applications.

III-b — SAD at end of a long branch

With the SAD connected at the end of a long branch circuit — as it might be if the goal were to determine the current surge delivery at a point of use, a legitimate concern for a user — the sharing can be expected to be quite different.

The MOVs, now upstream of the SAD, will take on a greater portion of the impinging current. When testing with a current generator, rather than the real-world scenario of a constant current source of the surges, the current delivered by the generator will be affected by the variable load resulting from different MOV locations.

To assess this situation, a second test series was performed, with the SAD now connected at the end of the 30-m branch. Only two values of MOV nominal voltage were investigated, at the extremes of the nominal voltage range, that is, 190 V and 205 V. The results of this test are summarized in Table 2.

Table 2
Current sharing between SAD connected at point 30 m and one or more MOVs connected at points 0 m, 3 m, and 10 m with 3 kA setting for available current

MOV nominal voltage (V)	Point(s) of connection of MOVs	Impinging current from generator (A)	Percent of impinging current captured by SAD †
190	0 m only	2460	5.7
	3 m only	1920	17
	10 m only	1400	41
	All three	2460	5.5
205	0 m only	2400	6.7
	3 m only	1880	18
	10 m only	860	41
	All three	2460	6.5

† Percentage computed for each case where the impinging current varies from 1400 A to 2460 A, depending on the MOV configuration.
Note that in this table, the percentages shown are the values captured by the SAD, not the MOVs.

The percentage values shown in Table 2 reveal the importance of the branch circuit inductances in limiting the propagation of the current surges. With an MOV at the service panel, the mechanisms of cascade coordination result in only a very small percentage of the impinging surge being captured by the distant SAD. Even if the MOV is connected on a different branch circuit, but a branch circuit shorter than that of the SAD, the percentage captured by the SAD remains low.

An even more important observation concerning this situation is the dependence of the captured percentage on the configuration and location of competing MOVs. In an actual installation, one can expect an ever-changing arrangement of user-installed, plug-in surge suppressors. Therefore, any measurement conducted at an intended point of use can only be a snapshot in time of a constantly changing situation. Making such a measurement, as stated previously, might be a legitimate attempt by the user to evaluate the surge threat at that location, but the results could be completely misleading.

Consequently, we must conclude that the only valid connection point of the transducer will be at the service entrance. This observation should be contrasted with measurements of voltage surges, for we know that their propagation suffers very little attenuation in a building wiring system [12].

IV. DIRECT PARALLEL CONNECTION

To assess the intrinsic "magnet" characteristic of the SAD, a test was performed to eliminate most of the inductive effects associated with the relative location of the MOVs and the SAD. In its commercial package, the SAD was provided with 30-cm long leads, probably the minimum practical length for installation in or near a service panel.

The MOVs used in the tests were simple components, not packaged, with their usual 2-cm long leads. To make a fair comparison with the SAD package, the MOVs were also fitted with a pair of 30-cm long leads, and then connected together at the point of injection of the surge. The same current-viewing transducers and digital signal analyzer used in the coordination tests were used to record the currents in the two parallel-connected SPDs.

In addition to the selected MOVs used in the first series of tests, other readily available MOV discs on hand in the laboratory included some lower ratings, with a known nominal voltage. These would have been unsuitable for connection to a powered 120 V system, but provided an opportunity to compare the "magnet" further down in the dynamic characteristic. Table 3 shows how the impinging current was divided between the two SPDs, and one example of recording is shown in Figure 4. The table can be interpreted as a comparison between the ability of the SAD and the ability of the MOVs to divert impinging surges.

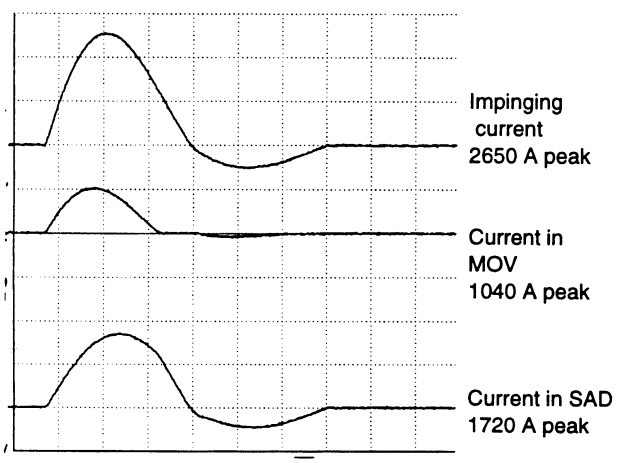
Table 3
Current sharing between parallel-connected SAD and MOVs with equal lead length, 3 kA 8/20 μs available short-circuit from the surge generator

MOV Rating (V rms)	MOV nominal voltage (V)	Current delivered by generator (A peak)	Percentage in MOV at peak †	Percentage in SAD at peak †
130	205	2540	25	86
	190	2540	30	83
95	147	2560	40	67
60	96	2700	68	34

† The two percentages add to more than 100% because the peaks are not simultaneous.

The 50% cross-over where the two devices have an identical performance is between the 95 V and the 60 V rating of the MOVs. In other words, one could say that the SAD, *in the current range of 1000 A*, behaves as an 80-V MOV would. However, Figure 4 also shows that the MOV reaches its peak earlier than the packaged SAD. This is probably caused by the additional internal inductance made necessary by the SAD design. In the case of the moderate rise time of the 8/20 surge, this slower response is not a problem, but might raise some questions in the case of surges with very short rise times.

At this point, our readers might wonder why the MOVs were characterized by their nominal voltage (voltage at 1 mA DC) but the SAD had not been so characterized. The answer is that the SAD, being a commercial package, is provided with condition-indicating lights that draw more than 1 mA at the rated line voltage, so that it is not possible to make the measurement of nominal voltage without going into the package to disconnect these auxiliary circuits. This arrangement is found in most commercial SPD packages, a regrettable situation that makes it difficult to assess any change in the condition of an SPD package after a long service or exposure to repetitive stresses.



Horizontal sweep (time): 10 μs/division
Vertical: variable, with computed values shown at right

Figure 4
Current sharing between SAD and 95 V rms MOV connected in parallel, 3 kA 8/20 available current

V. TEMPORARY OVERVOLTAGE IMMUNITY

As undesirable as they are, temporary overvoltages do occur in AC power systems, raising the issue of immunity to these events, especially in the case of a "low bidder." One condition that has been frequently reported is the loss of the neutral conductor in single-phase, four-wire 120/240 V systems.

Theoretically, the voltage across the side that has the lightest load can reach almost the full 240 V of the system. The more general case of some loads, albeit unbalanced, on both sides of the system can produce temporary overvoltages that equipment might sustain, undetected, for some time. Highly nonlinear SPDs are not so fortunate, to the point that the common wisdom is that most of in-service failures of SPDs are attributable to temporary overvoltages rather than to "large" surges.

Therefore, it would be desirable to assess the behavior of the SAD in case of moderate temporary overvoltages. In the case of severe temporary overvoltages, much of the equipment in an installation is likely to fail or cause tripping of overcurrent protective devices, so that a failure — in an acceptable mode — of the SAD would be taken in that perspective.

The SAD was exposed to two levels of temporary overvoltages: a sustained 125%, and a brief 150%. The waveform of the current drawn by the SAD under those conditions was monitored to detect any sign of incipient thermal runaway.

At 125% of rated line voltage, a noticeable peaking of the current was evident, and the housing became warm, but not hot to the touch. Due to limitations in the available laboratory test time, the test was not pursued beyond two hours, but it appears that the condition could have been sustained longer.

At 150%, peaking of the current was again quite noticeable, but without any sign of thermal runaway after two minutes of exposure to this severe overvoltage. The housing was hot, but without any sign of duress or hazardous condition. However, when the housing was opened for examination, it was found that several of the soldered diode connections had melted. Some diodes were loose in the housing. This condition would impact the ability of the SAD to continue its satisfactory performance as the "magnet", but nevertheless the reassuring absence of an objectionable failure mode was a positive result.

VI. DISCUSSION

The cascade coordination tests indicate that the initial concept of a simple, universal transducer that could be connected at any point of the power system was optimistic even as desirable as it was. Nevertheless, an SAD with field-demonstrated reliability can be used to serve as the magnet for attracting and characterizing current surges. The key to success — credible and useful measurements — is to make these measurements as close as possible to the service entrance.

Two configurations might be possible, depending on the physical arrangement of the conductors at the service entrance, as described in the following alternatives.

1. A package consisting of the SAD and a suitable current-viewing transducer inserted on one of the leads can be connected across the two active conductors. These connections would be similar to those routinely made for monitoring voltage surges with existing power quality monitors. Users of these monitors are quite familiar with all arrangements and precautions for such measurements.

   This arrangement makes it possible to wind more than one turn in the window of a high-frequency current transformer, thus providing sufficient voltage to the input of the power quality monitor.

   The disadvantage of this approach is that in a system where many MOVs might be connected on branch circuits, the "magnet" would capture only about 80 % of the impinging surge. Still, compared to the present total lack of information, 80% is not bad.

2. If it is possible to insert a current transformer on the incoming line — by a clamp-on type so as not to interrupt the loads — then the SAD can be connected, separately from the transducer, across the active conductors in the panel, downstream from the transducer. However, this arrangement limits the primary of the current transformer to one turn. Readily available high-frequency current transformers might not have a sufficiently high output voltage to ensure good resolution of the signal by presently available power quality monitors.

   While this approach has the advantage of the SAD capturing all the impinging surge, the simplicity of connecting an integral package simply across active conductors is lost.

VII. CONCLUSIONS

- The need for shifting focus from voltage surges to current surges has not decreased, if anything it is greater.
- The initial concept of providing a "magnet" to attract and measure current surges is applicable if the "magnet" is connected close to or at the service entrance.
- For an easy across-the line connection, the presence of many MOVs in the system might reduce the measured value to about 80% of the truly available surge current. While regrettable, this is not unacceptable.
- If a current-viewing transducer can easily be inserted upstream of the entrance service panel, then all of the available current surge will be recorded.
- ***Thus, the concept is still attractive and should be implemented in forthcoming power quality surveys.***

VIII. REFERENCES

[1] Martzloff, F.D., "Surge Recordings that Make Sense: Shifting focus from voltage to current measurements," Proceedings, EMC1996 Roma, 1996.

[2] Mansoor, A., Phipps, K., and Martzloff, F.D., "The Fallacy of Monitoring Surge Voltages: SPDs and PCs Galore!" *Proceedings, PQA'99 Conference,* May 1999.

[3] IEC 77A/301/CD – *Electromagnetic Compatibility – Part 4-30: Testing and measurement techniques – Power Quality Measurement Methods.*

[4] Martzloff, F.D., "Coordination of Surge Protectors in Low-Voltage AC Power circuits," *IEEE Transactions PAS-99*, January/February 1980.

[5] Standler, R.B., "Coordination of surge arresters and suppressors for use in low-voltage AC power circuits," *Proceedings, 1991 EMC Zurich Symposium,* 1989.

[6] Stringfellow, M.F. and Stonely, B.T., "Coordination of Surge Suppressors in Low-Voltage AC Power Circuits," *Proceedings, Open Forum on Surge Protection Applications, NISTIR-4657*, 1991.

[7] Hostfet, O.T., Hervland, T., Nansen, B., and Huse, J., "Coordination of surge-protective devices in power supply systems: Needs for secondary protection," *Proceedings, International Conference on Lightning Protection*, Berlin, September 1992.

[8] Lai, J.S. and Martzloff, F.D., "Coordinating Cascaded Surge Protection Devices: High-Low versus Low-High," *IEEE Transactions IA-29*, July/August 1993.

[9] Martzloff, F.D. and Leedy, T.F., "Selecting varistor clamping voltage: Lower is not better !" *Proceedings, 1989 EMC Zurich Symposium,* 1989.

[10] IEEE Std C62.33-1981, *IEEE Standard Test Specifications for Varistor Surge-Protective Devices,* Reaffirmed 1995.

[11] Harris Semiconductor Corp., "*Transient Voltage Suppression Devices,*" 1991.

[12] Martzloff, F.D., "Coupling, Propagation, and Side Effects of Surges in an Industrial Building," *IEEE Transactions IA-26*, March-April 1990.

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