On the Dispersion of Lightning Current After a Direct Flash to a Building

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Significance:
Part 2 – Development of Standards – Reality checks
Part 4 – Propagation and coupling of surges

Comparison between two simplified modeling studies of the dispersion and a documented case of the complexity of a direct flash to a residence.

Reservations on the justification of very high stress requirements for SPDs are expressed in a discussion, followed by a proposal to encourage more information sharing on the subject.

25th International Conference on Lightning Protection 5.10

ICLP 2000
Rhodes - Greece
18-22 September 2000

ON THE DISPERSION OF LIGHTNING CURRENT AFTER A DIRECT FLASH TO A BUILDING

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Abstract: Simplifications often made when simulating the dispersion of lightning current can yield results that depart too much from the complex reality of a direct lightning flash to a building. The unpredictable occurrence of side-flashes increases even more the complexity. Such simulations, if taken at face value, might lead to unrealistic specifications for service-entrance surge-protective devices (SPDs). A real-world anecdote illustrates both the complexity and a case where an SPD with only modest ratings, compared with some present proposals, provided satisfactory protection on the power-port appliances of a residence.

Key Words: Lightning current dispersion, side-flashes, surge-protective devices

1. INTRODUCTION

Recent discussions among participants in the development of surge-protection standards have shown a lack of consensus on the possible scenarios concerning the dispersion of the lightning current when a direct flash to a building is involved. Skepticism has been expressed both on the simulation of available paths for the dispersion, and on the magnitudes and waveforms postulated for the resulting currents flowing in the conductive elements of the installation — especially the service entrance surge-protective devices (SPDs). Note that the skepticism does not aim at the parameters of the lightning flash itself, which have been accepted now for many years [1], but at the simulation conclusions concerning requirements for service-entrance SPDs with very high current-handling capability.

Another objection has been that the distinction between a building equipped with a lightning protection system (air terminals, down-conductors and earthing system), on the one hand, and a building without such a system, on the other hand, might be misleading.

Every building that contains electrical circuits (power or communications), electrically-conducting mechanical elements, metallic structures, etc., has a de facto lightning 'protection' system of intended or unintended air terminals and down-conductors — except that their connection to the earthing system might have unpredictable and unwanted side effects.

As an input toward developing consensus, this paper reviews in a first part two examples of simulations that have been performed by others, and in a second part relates a real-world anecdote of a corroborated case of a direct flash to a residence.

2. SIMULATING DISPERSION

2.1 Examples of simulations

A Joint Working Group of the International Electrotechnical Commission (IEC) has recently developed a Technical Report on surge protection [2]. This four-year effort involved the participation of five IEC Technical Committees interested in the subject. The data base considered by the group included, among many sources, two published papers, identified in the Bibliography of the report, authored independently by members of the group.

In both studies, a 10/350 μs waveform was postulated, and a time-invariant earthing resistance and inductance were postulated. Currents in the available paths to earth and voltages at selected points of the systems were computed. For the purpose of this paper, three figures only are reproduced here for a qualitative glimpse on the results.

Figure 1, simplified from Ref [2], shows the nature of circuit components and configuration: two buildings and the distribution transformer linked by a cable in a linear arrangement. The point of strike is Building 1. The detailed numerical values, which are given in the referenced paper, are not significant for this comparison of the two studies.

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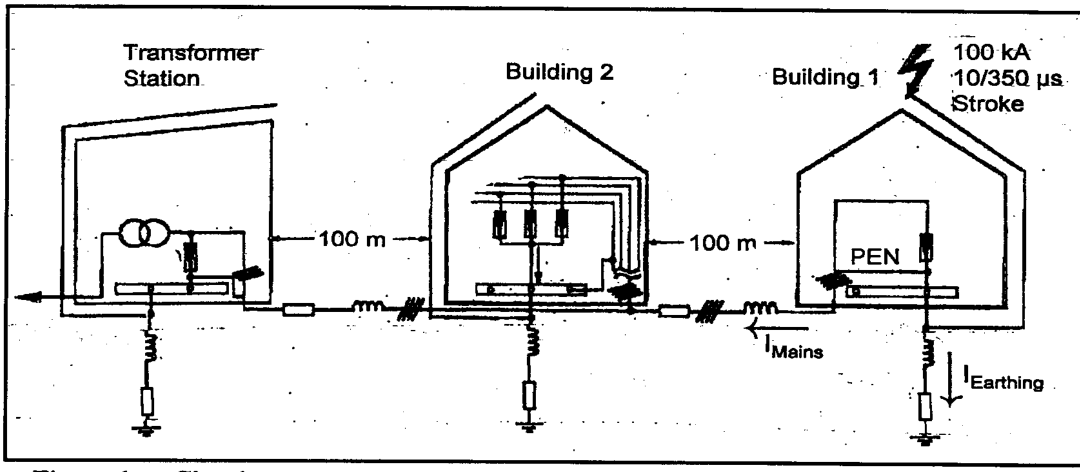

Figure 1 — Circuit components and configuration used in the Hasse simulation (Ref [2])

Figure 2 shows examples of the computed waveforms for currents at selected points of the Figure 1 circuit, from top to bottom : the postulated stroke current, the current ***exiting*** Building 1 via the power supply cable, the current in the earthing impedance of the building, and the current in the service-entrance SPDs of Building 2 resulting from the surge that is now, for Building 2, an ***impinging*** surge.

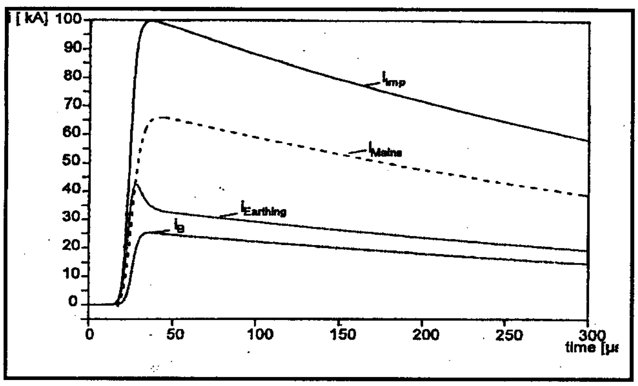

Figure 2 — Current dispersion for Figure 1

The numerical values are not significant, but the waveforms are. The current exiting the building (I_{Mains}) has the same waveform as that of the stroke. The earthing current ($I_{earthing}$) has an initial peak, due to the additional inductance of the power supply cable; in the long term, the inductive effect disappears, and the current division simply reflects relative values of the available earthing resistances.

In contrast with Figure 1 where the buildings are strung along a power supply cable, Figure 3, from Ref [3], shows a radial configuration of three buildings, each supplied by its own service drop, with all three connected directly to the terminals of the common distribution transformer. Varistor-type service-entrance SPDs are provided for each building. The transformer and each building have their own earthing electrode connection, represented by a fixed resistance and an inductance.

The radial service drops also consist of a resistance and an inductance, not drawn in the figure, but modeled in the computation according to the 20-m length of each radial drop. The point of strike of the flash is the earthing system of Building 1 (to which the neutral is bonded).

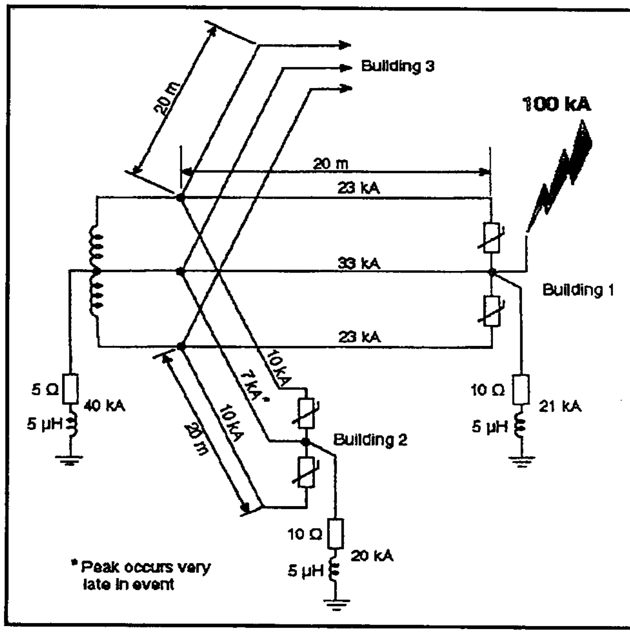

Figure 3 — Buildings configuration and resulting currents, according to Mansoor (Ref [3])

The significance of citing these two independent studies, separated by an ocean, by two different languages used by the authors, and by two different simulation programs, is that quite compatible conclusions were reached after exchanging information, first across the table during IEC working group meetings, then later on, via intensive e-mail messages, as a working relationship blossomed in spite of logistics barriers. This important point will be elaborated further in Section 7 of this paper.

With hindsight, it appears predictable that the initial current dispersion (the first ten microseconds) should be strongly influenced by the relative values of the postulated inductances, and the later dispersion by the relative values of the postulated (time-invariant) earthing resistances.

2.2 Involvement of service-entrance SPDs

The results of these simulations show that the stresses imposed on the service-entrance SPDs that become involved in dispersing the part of the lightning current toward remote earthing electrodes of the power distribution system will reflect the relative values of the earthing impedances. These stresses also vary with the postulated current waveform, ranging from the short 8/20 μs long-used for designing SPDs, to the more recent proposed 10/350 μs and finally to the seldom-considered continuing current within a multiple-stroke flash.

Performing these simulations was not a futile exercise but provided insight on the influence of significant parameters. However, among end-users, this complexity of postulates decreases the credibility of defining SPD requirements on the basis of simulations, giving a greater credibility to field experience of widely-used SPDs that have demonstrated satisfactory performance over many years.

3. SIDE FLASH

One event that contributes to the complexity and uncertainty of lightning current dispersion is the possible occurrence of a side-flash. A side-flash can establish unexpected paths to earth, with two consequences that extend beyond the consideration of service-entrance SPD stresses — the motivating concern for this paper.

- The side-flash itself can have hazardous consequences by acting as an igniter, as will be told in the anecdote of Section 4.
- The side-flash can cause currents to flow along conductive paths within the installation, thereby coupling transient overvoltages in the circuits of the installation, by common path or by induction.

Of course, the latter has the same end-result as what the bonding applied to avoid the side flash will produce, except for its unpredictability.

4. FROM SIMULATIONS TO REALITY

4.1 Setting the stage

To illustrate the credibility gap that separates reality from simplified representations, the following story should be narrated:

.... Once upon a time, in a far-away land (Upstate New York, U.S.A.) there lived an engineer who was recording surges, writing papers and presenting tutorials on surge protection, including the need for good bonding practices.

This engineer had bought a house from the previous owner who had lived many happy years there without any problem, so that our engineer made the (unwarranted) assumption that the house and its electrical wiring were in good order. The house was surrounded by several tall, mature trees so he thought that the cone of protection from the trees would benefit the house. Alas ! All-knowing Zeus recognized that this engineer needed to be taught a lesson on reality and thus sent a downward stepped leader toward the general area of the engineer's house ...

By now, dear readers, you have guessed that our mythical engineer is none but the author of this paper ... who will now offer this true story for your edification. First, the "where" : Figure 4 shows a simplified (here we go again ...) topology of the house, a two-story wood frame with basement and attic. Utilities (power, telephone, and cable TV), all entered, via overhead service drops, at the rear of the house, while water and sewer underground pipes were at the front of the house. The telephone system was not involved in the incident and therefore is not shown in the figure. The power installation included the usual revenue-meter (outside) and service panel (inside) with circuit breakers controlling a multitude of branch circuits. Only three are shown in the figure: lighting fixture in the attic, TV on the second floor, and a counter-top receptacle (via ground-fault interrupter) for the kettle (② in Figure 4) sitting on the enamelled cast-iron kitchen sink. (The significance of this detail will surface shortly.)

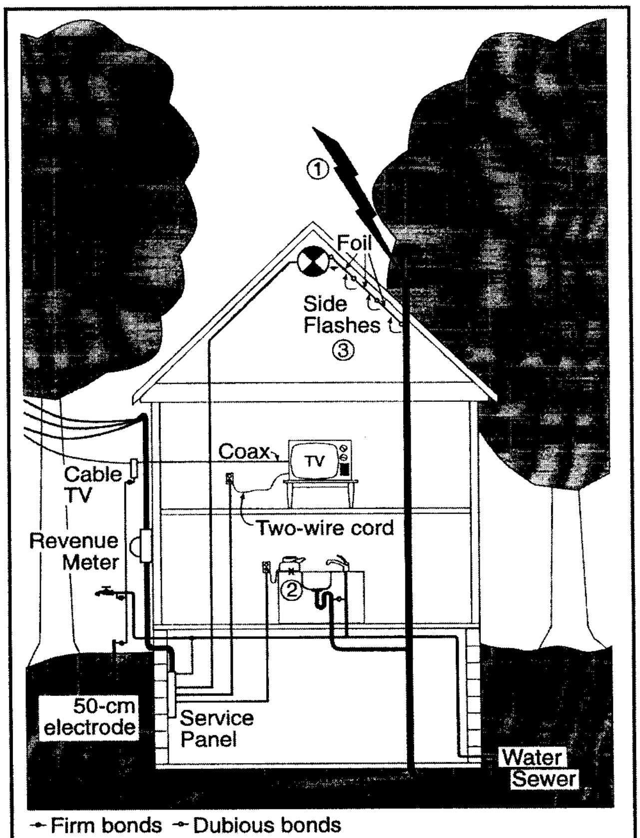

Figure 4 - Simplified configuration of anecdotal story

Water service and indoor piping were all copper, with a bond between the ground bus of the service panel and the nearest cold-water pipe. There was no visible grounding conductor to a (non-existent) made-electrode, but the perception existed that, given the vintage of the house (circa 1920), the water piping was sufficient, in addition to the multiple-grounded neutral of the power company.

Upon moving in the house, I had installed in the service panel a surge arrester (circa 1965 vintage) consisting of a silicon-carbide disk in series with a stamped-metal air gap. The cable TV service, as originally installed by the utility, only had a 50-cm long picket allegedly serving as "ground". Having been exposed to the concept of bonding, I had installed a bond between the picket and the nearby outdoor water faucet. A very passive — but soon to become active — part of the installation was the typical sewer system made of lead-bonded cast-iron pipe extending a to vent through the roof and connected to the street sewer, still with cast-iron pipes and thus offering the topology of a well-grounded air terminal, albeit below the peak of the roof. But I am getting ahead of myself, as I had never considered this vent as a lightning air terminal, since the house was surrounded by taller trees and thus "obviously" within their cone of protection.

4.2 Zeus' wrath

Now for the "When" and "How" : On the day when the tale unfolded, my wife (the corroborating eye-witness) and I were standing in the kitchen, listening to the approaching thunder and watching the big drops of rain just beginning to splash on the window. Then, a bright flash outside, with an immediate, deafening thunderclap, and also we both saw a small flash under the kettle. "That was a close one" we both said, whereupon I proceeded to check all appliances in the house. Several were inoperative, but a check of their branch circuit breakers revealed that they had tripped, and resetting them restored order. The only one that did not work was the old TV set, although there was no evidence of severe damage or burned smell, and we considered ourselves lucky — until a smell from the attic attracted my attention: the ceiling of the attic (which was covered by cellulose-base panels) was smoldering !

Fortunately — and not by accident — a handy fire extinguisher allowed me to quench the smoldering, while my wife called the fire department. To their credit, they were in front of the house within minutes. I told them that I believed that the fire extinguisher had done the job; nevertheless, one fireman proceeded to climb on a ladder to the attic window and hacked it away to let the smoke out, while another entered the house, pushing me aside, with a high power water hose in tow — which fortunately he did not turn on. After ripping several of the ceiling panels to verify that the fire indeed was out, the firemen left, with our emotional thanks and the applause of the neighbours gathered in front of the house.

4.3 The homeowner's epilogue

- One obsolescent TV receiver, which was not repaired, but catalysed the purchase of a new and upgraded set (missing the opportunity to do an extensive post-mortem as in the "*Case of the Cozy Cabin*" [4]).
- Several hundred dollars expended to repair the window destroyed by the firemen, install a splice on one attic rafter weakened by charring, and replacing the ripped panels.
- After recovering from the shock, a realization of how lucky to have been in the house at the time of the incident, and glad for the foresight of having a fire extinguisher on every floor of the house !

4.4 The engineer's epilogue

Such a traumatic experience called for an investigation of the incident. The first observation was that the previous owner had installed insulation between the attic rafters, stapling the aluminum foil of the bats to the rafters, but not overlapping them across the edges of the rafters. This arrangement, concealed by the panels, created several gaps along the 5-m distance separating the sewer vent pipe from the light fixture at the apex of the attic, but reducing the total gap to a few centimetres — an easy side-flash scenario, resulting in the ignition of the dust and surface fuzz of the rough-from-sawmill rafters.

The second observation, a few days after the incident, was to notice a small rust spot on the kitchen sink where the kettle usually sat: there was a small hole in the otherwise good-condition glaze, exposing the underlying cast iron: The flash seen under the kettle (②) was the cause of the enamel puncture; several kilovolts must have been required to break down the series-connected insulation of the heating element inside the kettle, and the porcelain glaze of the sink. The electronic ground-fault circuit breaker controlling the receptacle had to be reset, but it was not damaged, and subsequent use of the kettle did not cause it to trip, so we concluded that the brief breakdown of the insulation of the heating element was not a massive event.

The immediate action was to install a bond between the sewer vent pipe and all extraneous metal in the attic. The long-term effect on the engineer was a consciousness-raising on the issue of surge protection of multiple-port appliances, even though a bond had been provided between the incoming cable TV service and the power system [5]. At that time, the concept of the surge-reference equalizer [6] had not yet surfaced, and no commercial device was available to provide that function. In fact, the proliferation of plug-in surge-protective devices launched by the introduction of metal-oxide varistors had not yet occurred.

A casual inspection of the fist-sized surge arrester at the service panel showed no distress, an indication of adequate design for the rare scenario of a direct strike to a building [7].

This arrester used only a 30-mm diameter silicon carbide disk as varistor, which most likely would be destroyed by the high-energy lightning surges presently considered or recommended by some IEC committees. (Sorry, the house has changed owners and an exhaustive test on that particular surge arrester, desirable as it would be in retrospective, is not possible.)

The attic side-flash (③ in Figure 4) clearly indicated that the sewer vent pipe was the point of strike (①), raising the question of why the tall trees failed in their expected mission of establishing an effective cone of protection. Perhaps one explanation might be that during the initial part of the rainfall, the still-dry trees could not emit a successful competing upward streamer, compared to the well-grounded cast-iron pipe. Comments from lightning physics experts on this speculation would be welcome.

Thus, our engineer had learned his lesson, and lived happily without further incident for fifteen more years in the far-away land. However one cannot say 'lived happily ever after' : After moving to a new home further South, one night a nearby lightning flash triggered a burglar alarm (which had to be pried open to silence the horn turned on by a failed semiconductor, at 02:00 am no less) and damaged a remote-control garage door opener: Zeus had still kept track of the battle-hardened surge-protection engineer, but that is another story ...

5. FROM REALITY TO SIMULATION

Among several investigations based on rocket-triggered lightning, the ongoing effort at Camp Blanding in Florida, U.S.A. is aimed at injecting a lightning current at specific points of the replica of a residential power system. Initial results (1997) were inconclusive because of instrumentation problems, but as these are progressively overcome, more definitive information becomes available. Actually, the most recent report [8] provides so many raw measurement results that an effort of synthesis will be necessary to gain a better understanding of the issues.

The major advantage of such systematic projects over a random recitation of anecdotes could be the possibility of going from a real-world configuration to a sufficiently detailed numerical representation of the circuit parameters. A cross-validation of the measurement results and of the simulation results would then significantly increase the credibility of both, and lead to realistic designs and ratings for SPDs.

The challenge, of course, will be to represent enough of the many, many parameters involved in the real world but not so many as to make the simulation model unmanageable. For instance, the real-world situation of the anecdote already simplified in Figure 4 — with the ill-defined bonds and side-flashes — would be difficult to turn into a manageable and credible simulation.

6. DISCUSSION

The simplified assumptions on lightning current dispersion illustrated in Section 2 have met with some skepticism among the North-American surge-protection community and perhaps others. Part of this skepticism is also based on the relatively rare occurrence of massive failures for secondary arresters (distribution transformer secondary terminals and residential service entrance) designed to withstand the "classical" 8/20 μs or 4/10 μs surges, at crest levels of a few to a few tens of kiloamperes. Furthermore, the two simulations cited in Section 2 were based on the assumption that earthing electrodes have a constant resistance during the flow of the lightning current, an assumption that is questioned on the basis of preliminary results of measurements made in Florida in connection with triggered lightning experiments [8].

In contrast with these simplified scenarios, the real-word anecdote would be a challenge for any numerical modelling but demonstrates evidence of substantial overvoltages developed in the installation (insulation puncture at the kettle) during the flow of this undetermined lightning current dispersion among the complex available paths to earth. The anecdote also offers an example of a surge arrester with modest current-handling capability surviving the scenario of a direct strike to a building.

A symptom of the incomplete consensus is the noticeable lack of a discussion of risk analysis in the report developed by the IEC Joint Working Group [2]. This topic was initially included in the document outline, raising high expectations, but, confronted with incompatible proposals, the group gave up on that initiative. The proposed methodologies ranged from elaborate and detailed mathematical formulae — which turned out to be using somewhat arbitrary postulates — to common-sense, almost intuitive considerations.

7. A PROPOSAL FOR THE DISPERSION OF LIGHTNING INFORMATION

In a 1963 freedom-seeking speech that still resonates today, the mantra *"I have a dream"* was coined. On a much more modest scale, the author has a dream of unfettered information-sharing on lightning. Having cited the preceding examples of developing, but still incomplete, consensus on the dispersion of lightning current, here is the proposal (or is it a challenge ?): Hopefully helpful timely participation, on a world-wide basis via electronic mail could supplement — not compete with — the established routes for information sharing, at a much accelerated pace. We are still mostly in a mode of developing standards — a notoriously slow process — by volunteers or delegates often hampered by travel budgets, or of publishing peer-reviewed papers — unquestionably a wise process, but entailing long delays between generation and ultimate publication of the information.

This process of information dispersion might take one of the many forms by which the Internet has revolutionised information sharing. Should this paper be accepted for oral presentation at the Conference, the author would propose to make only a very brief summary of the paper itself — available to all in print — and make use of the scheduled presentation time for a cross-pollination of ideas among the attendees (much superior to the one-on-one poster process) on how to implement the proposal, bringing reality to the dream. Pessimists will point out hurdles such as the requirement of "previously unpublished information" for later acceptance of an archival paper reporting research on the subject, or the understandable modesty of researchers who want to be sure that the work is complete before publishing even preliminary results, and so forth. Optimists will find ways to by-pass these hurdles and broaden an early consensus.

8. CONCLUSIONS

- While there is no disagreement, or at least very little skepticism, on the specific parameters of the lightning discharge, consensus on the implications of lightning current dispersion for the rating of surge-protective devices has not yet been reached.
- Anecdotal information offered in many countries on their experience with service entrance surge-protective devices having moderate handling capability suggests that the proposed ratings for very high duty levels might be unnecessary and not cost-effective, unless a convincing risk analysis demonstrates otherwise.
- Information dispersion on these issues could be greatly enhanced by establishing an informal and time-sensitive world-wide site (in parallel, not in conflict with more formal procedures), which the author is prepared to undertake if encouraged and supported by colleagues in the lightning-protection community.

9. REFERENCES

9.1 General

Many publishing organizations, in their instructions for the peer-review process, raise the question "Are references adequate to show knowledge of work by others?" or words to that effect. While undoubtedly a valid question, the result is sometimes a lengthy recitation of up to several hundred citations, which seems an overkill.

Standard-writing organizations have evolved the concept of differentiating between, on the one hand ***"References"*** — a listing of documents that are made an integral part of the standard by a ritual introductory statement, and, on the other hand, ***citations*** — in the form of a "Bibliography" with or without annotations.

For this paper, "References" are limited to the strict minimum necessary to support a particular point being made. To illustrate where extensive listing of "references" might lead, a literature search was conducted with "lightning" as a leading key word, and next with one additional word. The results are listed below, showing the number of "hits" found for the period of just 1969-1999 — the accessible on-line data base did not include Benjamin Franklin's seminal letters to the Royal Society on lightning protection of houses and the Purfleet munitions storage [9].

Lightning	15 791
Lightning + surge	2348
Lightning + current	3306
Lightning + damage	1130
Lightning + protection	6349
Lightning + arrester	1816
Lightning + earth + electrode	139

These numbers show that it would be unrealistic for a single researcher to examine in detail the contents of fifteen thousand papers. Injecting the concerted filtering and sharing action of today's active researchers into a readily accessible data base — the author's dream — would be a great improvement.

9.2 Specific references

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