



# Comparison of the SAFE\_AIR code numerical results against wind tunnel measurements on a two-stack waste incinerator model

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## Abstract

The SAFE\_AIR code simulates the transport and diffusion of airborne pollutants. This Lagrangian dispersion code is based on the advection of Gaussian segments and puffs driven by a 3D diagnostic wind model, able to deal with both non-stationary and inhomogeneous conditions. SAFE\_AIR is an evolution of the AVACTA II code, "recommended" by the U.S. EPA. In this paper, results obtained by means of SAFE\_AIR are compared against measurements concerning plume dispersion experiments on a small scale model of a waste incinerator with two stacks. These experiments were carried out in the developed boundary-layer wind tunnel property of CRIACIV (Centro di Ricerca Interuniversitario di Aerodinamica delle Costruzioni ed Ingegneria del Vento) placed in Prato, Italy.

## 1 Introduction

The use of wind tunnel measurements is an essential step as far as a complete model evaluation process is concerned (e.g., Schatzmann and Leitz [1]).

Some model evaluation exercises concerning the SAFE\_AIR code (Simulation of Air pollution From Emissions \_ Above Inhomogeneous Regions,



Canepa and Ratto [2]; Canepa et al. [3, 4]; Canepa [5]) were already performed (e.g., Canepa and Bultjes [6]; Canepa et al. [7]). In this work, we applied the SAFE\_AIR code to some of the experiments carried out in the CRIACIV developed boundary-layer wind tunnel (Corti et al. [8]).

The CRIACIV experiments, performed in neutral atmospheric stability conditions, concerned a 1:400 scaled waste incinerator model with two parallel stacks 0.15 m tall (60 m at full scale). Special attention was devoted to the simulation of both the building downwash phenomena (using different angles for wind direction) and the reflection of the pollutant at the terrain and at the boundary-layer edge. Different concentration measurements like ground level concentrations (GLC), vertical and horizontal concentration profiles at different distances downwind of the stacks were performed. In order to perform such measurements, CRIACIV wind tunnel has been equipped with a system that allows tracer mean concentrations in gaseous samples to be measured. The systems is based on a Flame Ionisation Detector (FID) and allows 12 samples of gas, containing a known tracer, to be taken from different positions inside the tunnel and analysed on-line so that the average concentration can be evaluated with reference to previous calibrations of the FID unit.

## 2 The SAFE\_AIR code

The SAFE\_AIR code is extensively described in Canepa and Ratto [2], Canepa et al. [3, 4], and Canepa [5]. It is an evolution of the AVACTA II code (Zannetti [9]), recommended as "alternative model" by U.S.EPA. SAFE\_AIR is included in the Model Database of the European Topic Centre on Air Quality (<http://aix.meng.auth.gr/lhtee/database.html>). A commercial version of SAFE\_AIR is distributed by FiatLux Publications, Fremont, California, USA (<http://www.envirocomp.org/html/news/safe-air.htm>).

SAFE\_AIR consists mainly of two parts: a meteorological pre-processor (WINDS, Wind-field Interpolation by Non-Divergent Schemes) and a pollutant diffusion simulator (P6, Program Plotting Paths of Pollutant Puffs and Plumes).

The meteorological pre-processor WINDS (Ratto et al. [10]; Ruaro et al. [11]; Ratto [12]) computes the wind field necessary for the subsequent description of the transport of the pollutant plume above complex orography. WINDS is a mass-consistent model (Ratto et al. [13]) developed at the Department of Physics of the University of Genoa, Italy, in collaboration with Prof. D.P. Lalas [14].

P6 is a model derived (Canepa and Ratto [2]; Canepa et al. [3, 4]; Canepa [5]) from the part of the AVACTA II code simulating airborne pollutant dispersion. P6 is a Lagrangian multisource model based on the Gaussian formula in which the plume is broken into independent elements (either segments or puffs). Pollutant dynamics are described by the evolution of plume elements according to local meteorological conditions. This method offers the advantage of maintaining the simplicity of a Gaussian formula, while allowing a



more accurate numerical simulation of both non-stationary and inhomogeneous conditions. Segments provide a numerically fast simulation of dispersion of air pollutants near their source during transport conditions. Puffs allow a proper simulation of diffusion, both far from the source and during calm or low-wind situations. P6 is able to simulate at the same time both the stack tip and building downwash phenomena following the Briggs method [15]. As far as the simulation of the reflection term is concerned, besides partial reflection methods, the total reflection Yamartino method [16] is implemented.

### **3 Small scale model characteristics and experimental set-up**

At small scale, a 0.7 m high neutral boundary-layer was developed by using a spire vortex generator at the tunnel inlet and roughness elements, with variable height from 10 to 50 mm (the shortest ones are closer to the model), covering the entire tunnel length. Different layout of roughness panel and spire dimensions were tested in order to obtain a correct wind profile. With the final layout of the wind tunnel turbulence promoters, an average wind speed profile with a power-law exponent equal to 0.19 has been obtained.

The subject of the study is a waste incinerator complex placed about 30 km far from the sea in the north of Italy. The incinerator covers an area of about 500 by 250 m with two identical stacks, 60 m tall and 1.5 m in diameter. A complex of buildings of different sizes, for waste storage and treatment, are placed around the stacks and influence plume dispersal. At a preliminary phase of the study, a Gaussian dispersion model (US-EPA ISC3ST [17]), modified for the wind profile parameter (mean wind profile exponent), was used to evaluate approximately the dispersion effects of the main pollutants over the area at ground level. Consequently, an adequate scale (1:400) was selected for the wind tunnel measurements, considering both the available dimensions and the necessity of a good geometrical representation. This scale allows studying diffusion in an equivalent 2-km radius downwind of the stacks. Hereafter all measurement are intended at full scale if not otherwise specified.

For a complete evaluation of the ground-level pollutant concentrations for different conditions of wind directions, different orientations of the model were studied using a rotating table. Average conditions for wind velocity were considered corresponding to a velocity of about  $5.8 \text{ m s}^{-1}$  at 10 m height.

Measurements have been carried out with a system that allows tracer mean concentrations in gaseous samples to be measured [8].

Data collected is successively analysed in order to obtain the average tracer concentration for the stationary emission. The time interval for averaging was 4.5 minutes at small scale, while the time scale factor is about 3600, thus this averaging time is more than enough to allow a comparison with the results of simulations of codes dealing with hourly average concentrations at full scale.

A non-dimensional concentration field is obtained normalising the measured concentrations,  $C$  (expressed in  $\mu\text{g m}^{-3}$ ), by means of:

$$\text{Normalised concentration} = C U_{\text{ref}} H^2 / Q$$

where  $U_{\text{ref}} = 11.3 \text{ m s}^{-1}$  is the reference flow speed evaluated outside the boundary-layer,  $H = 280 \text{ m}$  is the boundary layer depth, and  $Q = 17.10 \text{ g s}^{-1}$  (that is to say  $8.55 \text{ g s}^{-1}$  for each stack) is the total tracer emission rate.

## 4 The performed simulations

We reconstructed the wind field inside the wind tunnel using the WINDS code; then the concentrations were simulated using the P6 code. We selected a domain having the X-axis along the wind tunnel centerline and measuring  $4000 \times 1000 \times 640 \text{ m}^3$  around the sources. This domain was digitized in the horizontal plane by mean of  $160 \times 40$  grid points and, along the vertical direction, by 12 conformal levels (WINDS code) or 100 Cartesian levels (P6 code).

Like in Manfrida et al. [18], the complex of buildings of different sizes placed near to the stacks was schematised as a parallelepiped with horizontal dimensions  $50 \times 50 \text{ m}^2$  and 27 m tall (see Figure 1). The stacks were placed, along the X direction, 500 m far from the west domain edge and, along the Y direction, equidistant with respect to the domain centerline. Our study concerned the wind direction showed in the Figure 1 only.

We simulated by means of the WINDS code the horizontally homogeneous wind field in the wind tunnel assuming a wind speed of  $5.8 \text{ m s}^{-1}$  at 10 m a.g.l. and of  $11.3 \text{ m s}^{-1}$  ( $U_{\text{ref}}$ ) at 280 m a.g.l. (boundary layer depth). We used a roughness length of 0.3 m and the Pasquill stability class D (neutral conditions) was imposed.

Among the measured concentrations performed, we simulated by means of the P6 code the ground level (4.8 m a.g.l.) concentrations only. We treated a total of 55 ground level simulated and measured concentrations distributed on 5 horizontal parallel segments. One of them was placed along the plume centreline; the four remaining were placed at the distances of 54 and 126 m, on the right and on the left of the central one. We simulated the plume rise, taking into account both stack tip and building downwash phenomena, using the Briggs method [15], obtaining an effective emission height of about 90 m. The reflection of the tracer at the terrain and at the boundary-layer edge was simulated by means of the Yamartino method [16].

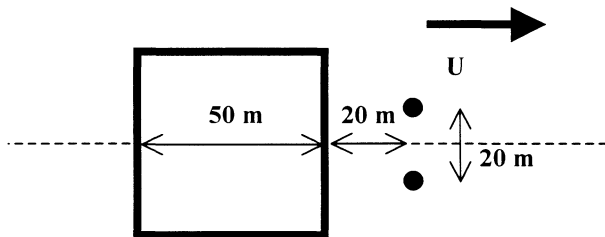


Figure 1: Wind direction (➡), sources (●), domain centerline (---), and schematized building geometry (□).

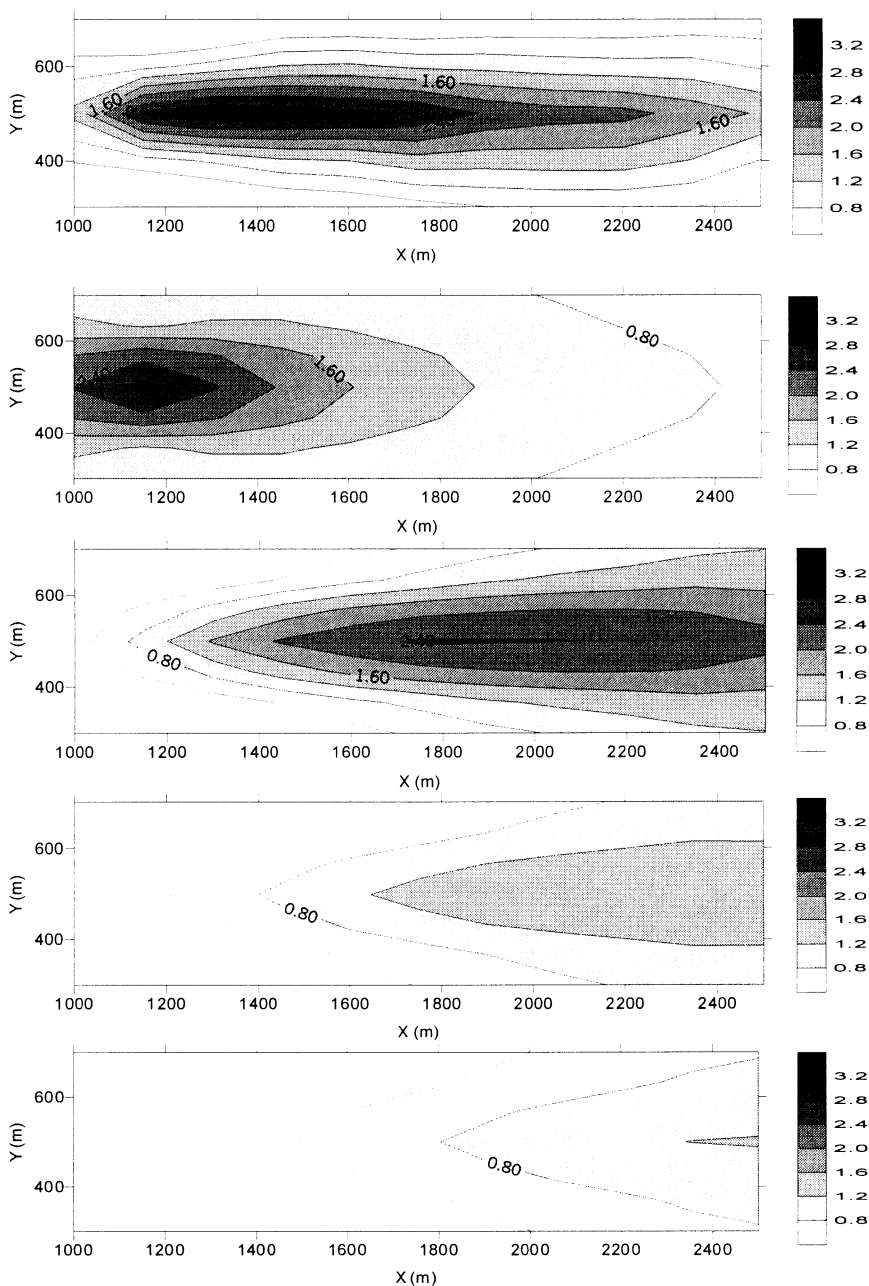


Figure2: Ground level normalised concentration maps in the domain share where measurement are available, from the top to the bottom: experimental results; simulation results obtained using the Briggs urban, Brookhaven, Briggs open country, and Pasquill-Gifford-Turner  $\sigma$ -function, respectively.



Figure 2 shows a comparison among the normalised ground level measured concentration map (on the top) and the corresponding simulated concentration maps (below) obtained using the Briggs urban, Brookhaven, Briggs open country, and Pasquill-Gifford-Turner  $\sigma$ -function respectively. The considerable dependence of the code performance on the kind of  $\sigma$ -function used is evident, but in all cases the width of the simulated plume is greater than that of the experimental one. From the reported results it is possible to see that the best compliance to measured data, as far as the estimate of entity of the maximum and the tracer pattern is concerned, is obtained using the Briggs urban and Brookhaven  $\sigma$ -function, respectively.

Comparison between experimental and simulated ground level concentration profiles on plume centreline (top), and off-axis profiles (middle and bottom) is shown in Figure 3. Considerations similar to those concerning Figure 2 can be drawn. Furthermore, one can notice that the off-axis profiles taken at the same distance from the plume centreline show some differences, this is due to the experimental measurement uncertainty estimated to be about 15% by Manfrida et al. [18]. In any case it is clear that the experimental concentrations behaviour is a middle course between the simulated ones using the Briggs urban and Brookhaven  $\sigma$ -function.

Before calculating the values of the statistical indices reported in Table 1, we pre-processed the ground level data in order to try to deal with measurement uncertainty. In more detail we calculated the average measured concentration values for both the couples of off-axis profiles taken at the same distance from the plume centreline. Then we compared such average values with the corresponding simulated ones.

The values of the FB index show that SAFE\_AIR underestimates on average the measured concentrations in all cases (the Pasquill-Gifford-Turner  $\sigma$ -function gives the biggest underestimation entity).

From the FS values, one can argue that the spreading of the concentration values obtained with SAFE\_AIR is lesser than the spreading of the observed ones. This behaviour is much evident for the Pasquill-Gifford-Turner  $\sigma$ -function again.

As far as the FA2 index is concerned the Brookhaven  $\sigma$ -function gives the best result, but the result obtained using the Briggs urban  $\sigma$ -function is good enough as well.

The values of the NMSE, WNNR and NNR indices are lesser for the Briggs urban and Brookhaven  $\sigma$ -function than for the Briggs open country and Pasquill-Gifford-Turner  $\sigma$ -function. In more details, as far as the previous three indices are concerned, the best results are obtained using the Brookhaven  $\sigma$ -function. This behaviour is more evident in relation to NNR, which means that the Brookhaven  $\sigma$ -function is more efficient than the Briggs urban  $\sigma$ -function in particular as far as the estimate of low level concentrations is concerned.

In any case, examining the six statistical quantities as a whole, one can confirm that using the Brookhaven  $\sigma$ -function SAFE\_AIR give better results than using the three other  $\sigma$ -functions.

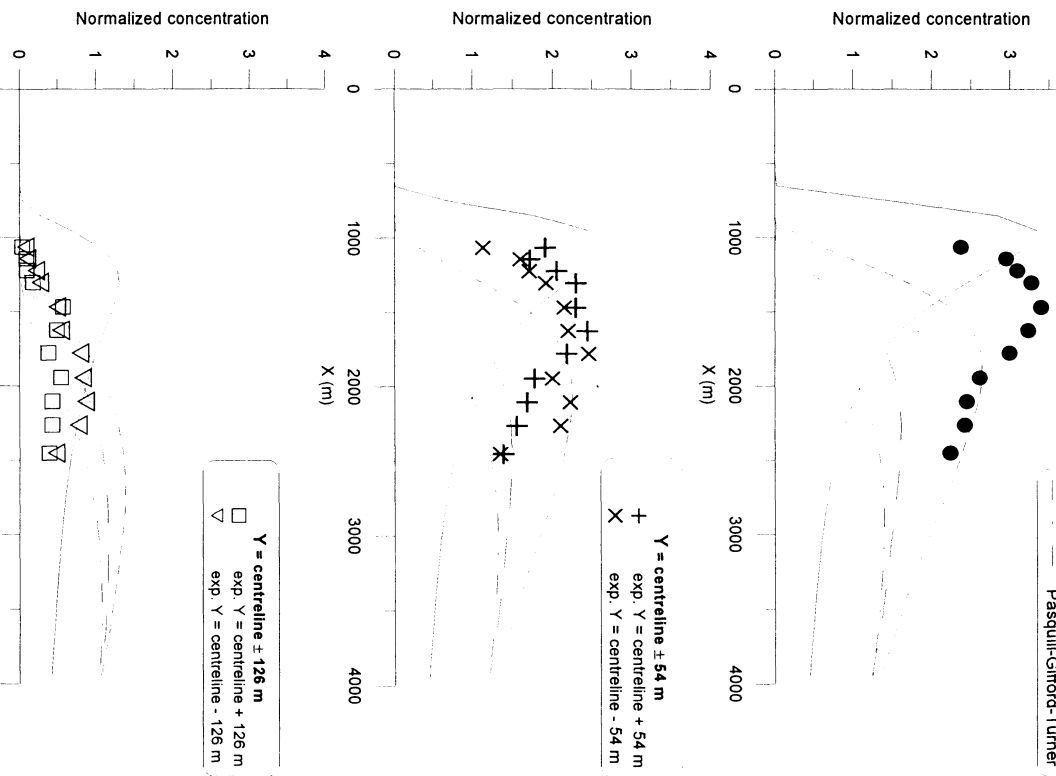




Table 1. Statistical indices: comparison between a hypothetical perfect model values and the SAFE\_AIR model values obtained using the Briggs open country, Briggs urban, Brookhaven, and Pasquill-Gifford-Turner  $\sigma$ -function for simulating all the ground level concentrations.

|             | FB   | FS   | FA2  | NMSE | WNNR | NNR  |
|-------------|------|------|------|------|------|------|
| perf. mod.  | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 |
| Briggs o.c. | 0.66 | 0.58 | 0.44 | 1.18 | 1.32 | 0.76 |
| Briggs u.   | 0.04 | 0.39 | 0.60 | 0.37 | 0.38 | 0.46 |
| Brook.      | 0.13 | 0.17 | 0.73 | 0.28 | 0.32 | 0.27 |
| P.-G.-T.    | 1.06 | 0.79 | 0.33 | 2.91 | 3.11 | 1.74 |

## 5 Conclusions

We compared the SAFE\_AIR performance against ground level concentration measurements concerning dispersion experiments on a small scale model of a two-stack waste incinerator, carried out in a developed boundary-layer wind tunnel.

Results show appreciable differences between the simulated ground level concentrations obtained using different  $\sigma$ -functions. The Brookhaven  $\sigma$ -function, that has been derived from elevated releases (about 110 m) over quite rough surface (about 1 m), gave on the whole the best result, even if the calculated effective height of the plume and wind tunnel roughness length are, respectively, about 90 and 0.3 m only (at full scale). The result obtained using the Briggs urban  $\sigma$ -function, which has been derived from several urban dispersion experiments (big roughness lengths) with low level tracers, is particularly appreciable as far as the simulation of the entity of the normalised maximum concentration is concerned (a simulated value of 3.23 against the measured one of 3.40). On the contrary, the Briggs open country  $\sigma$ -function, which in neutral cases is similar to the Pasquill-Gifford-Turner one that has been derived from low level releases over quite smooth surface, provided worst result.

As a conclusion we can affirm that the SAFE\_AIR code performed fairly satisfactory, in neutral atmospheric conditions, but the choice of the  $\sigma$ -function is very critical. Then, before application of the code, preliminary calibration exercises are advisable. Furthermore, the incorporation in SAFE\_AIR of  $\sigma$ -functions able to connect directly the pollutant diffusion to the main characteristics of the turbulence, is desirable.



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# DEVELOPMENT AND APPLICATION OF COMPUTER TECHNIQUES TO ENVIRONMENTAL STUDIES VIII

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## PREFACE

The Envirosoft conference cycle started in 1986 with the first conference in Newport Beach, California. It is amazing to consider how much progress has been made since then and how many things have changed in the field of “envirometrics”.

Back then, many environmental scientists were still uneasy with computers and hesitant about using them. The personal computer revolution had just started – the first Macintosh had been launched in 1984, even though more primitive PCs had been around for several years. Many colleagues were still wondering whether or not we really needed computers to study the environment and only a relatively small segment of the environmental scientists – the computer “modelers” – were enthusiastic about this relatively new tool. Computers were expensive, slow, and difficult to use. And you could still hear many old-fashioned scientists telling the new generation that computer simulations and results could not be trusted ... you could only trust the human brain – theirs, of course.

Today, after the PC revolution and, more recently, the Internet revolution, everything has changed. The use of computers in environmental sciences is paramount. Now, virtually anybody can afford to buy a PC with the same computational power of a multi-million dollar supercomputer of the mid-1990s. Everywhere, by use of a simple phone line one can access the World Wide Web, to work and interact globally, and to share data, software, and information daily. And this is just the beginning...

Today, environmental concerns are a top priority in the agendas of politicians, planners, developers, regulators, and industrialists. Compliance with environmental regulations is one of the key factors in urban and industrial development, particularly in the free-market societies in Western Europe and North America. In these countries, the environmental improvements in the last 30 years have been enormous, at least for industrial pollution. But the growth of transportation emission (i.e., the pollution generated by the cars) has created and is creating new problems and challenges. There is now a greater awareness of global issues and dangers, i.e., the concrete possibility of future global changes caused by anthropogenic activities on earth.

In summary, never before has environmental and computer sciences been so important in our life. Both fields are at their peaks and there is no reason to believe that public interest and scientific concern will decline. The Envirosoft conference cycle was the first major international event fully dedicated to covering the



intersection of these two major fields of science. We are proud we had the vision, two decades ago, to direct our efforts along this direction and provide the scientific community with a unique forum for discussion on computer methods and applications in environmental sciences.

What are our challenges for the future? There are many, but let's just mention three key issues: ethics, professional growth, and the globalization challenge.

On ethics, we must remember that we are – more than anything else – environmental *scientists* and must insist on the use of the scientific method above all special interests and preconceived opinions. Our environmental concerns should not become a religion, an ideology, or a cult. Scientific objectivity, a high degree of professional ethics, and the continuous re-evaluation and comparison of scientific evidence and available data should be the pillars of our daily work.

On professional growth, we should not hesitate to embrace new technology. Let's not repeat the mistakes made by so many scientists in previous generations. Hardware and software developments are proceeding at an incredibly fast rate today. We should not hesitate in adopting new software, exploring the newest Internet features, or experimenting with virtual reality hardware. Ten years from now, the use of light and comfortable human-machine interface devices may become as common as the mouse we all use today.

Finally, on the globalization challenge, we simply should not be afraid. The Internet revolution will change the way we work, the way we employ and retain people, the way we compete for jobs and careers, the way we teach and are taught, and the way we reward and are rewarded. Much scientific work – even of a high technical nature – will be performed through the Internet by people hired just for specific projects or tasks and by project teams scattered throughout the world. For environmental scientists, globalization will mean the possibility of offering their special skills on a global scale. Those who are not afraid of these changes will be the leaders of tomorrow.

We would like to thank the participants and the International Scientific Advisory Committee for all their hard work. We would also like to acknowledge The Bilbao Engineering School, which is part of the University of the Basque Country, for kindly allowing us the use of their School to hold Envirossoft 2000.

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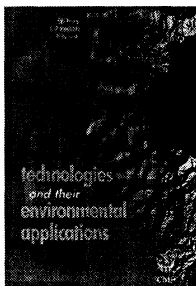
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