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INTERNATIONAL ASSESSMENT OF PCA CODES*

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BACKGROUND AND OBJECTIVES OF THE ASSESSMENT EXERCISE

Over the past three years (1991-1993), an extensive international exercise for intercomparison of a group of six Probabilistic Consequence Assessment (PCA) codes was undertaken. The exercise was jointly sponsored by the Commission of European Communities (CEC) and OECD Nuclear Energy Agency. This exercise was a logical continuation of a similar effort undertaken by OECD/NEA/CSNI in 1979-1981.[1] The PCA codes are currently used by different countries for predicting radiological health and economic consequences of severe accidents at nuclear power plants (and certain types of non-reactor nuclear facilities) resulting in releases of radioactive materials into the atmosphere. The codes participating in the exercise were: ARANO (Finland), CONDOR (UK), COSYMA (CEC), LENA (Sweden), MACCS (USA), and OSCAAR (Japan).

In parallel with this inter-code comparison effort, two separate groups performed a similar set of calculations using two of the participating codes, MACCS and COSYMA. Results of the inter-code and inter-MACCS comparisons are presented in this paper. The MACCS group included four participants: GREECE: Institute of Nuclear Technology and Radiation Protection, N.C.S.R. "Demokritos"; ITALY: ENEL, ENEA/DISP, and ENEA/NUC-RIN; SPAIN: Universidad Politecnica de Madrid (UPM) and Consejo de Seguridad Nuclear; USA: Brookhaven National Laboratory, U.S. NRC and DOE.

The main objective of the assessment program was to analyze the results produced by the different codes, and explain the major differences in the results in terms of modeling of physical events and various radiological exposure pathways including the food chain pathway. **Since the calculations were not performed for a specific geographic location, the results predicted by all codes and presented in this paper have no absolute significance outside of the scope of the code comparison.**

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*This work was performed under the auspices of the U. S. Nuclear Regulatory Commission.

The specific objectives established for the exercise were as follows:[2,3]

a) to compare the predictions of the participating codes under a range of conditions,
b) to contribute to Probabilistic Consequences Analysis (PCA) code quality assurance programs,
c) to guide future developments in the PCA field by identifying the merits and appropriate use of different methods,
d) to enhance the general appreciation of the applicability of PCA codes by those who develop and use them, particularly in decision-making and regulatory processes,
e) to provide a forum for discussion on various international approaches to PCA model and code development, and to encourage harmonization of codes,
f) to provide a forum for exchange between code users and developers, and
g) to produce a report on the exercise which will act as a basic PCA code comparison reference.

The purpose of the paper is to outline the scope and some details of this PCA code assessment exercise and illustrate the results of comparisons using predictions of several selected end-points for dose, health, and economic consequences for some selected cases.

SPECIFICATIONS

The participants were provided with a comprehensive set of input specifications describing a fictitious site with the surrounding area extending to 2000 km from the point of release. The data included population and agriculture/economic distributions, and site meteorology.

Although all PCA codes participating in the exercise had many similarities in the approach to modeling of the major phases of consequence calculations (meteorological sampling, materials dispersion/deposition, dose/health effects predictions, and economic consequences), there were some differences in the input data requirements. It was recognized at the outset of the project that an attempt to satisfy specific requirements of all codes would lead to a prohibitively large volume of input data and still would not eliminate some inherent ambiguities in the input data interpretation. Therefore, the designers of the input specifications chose to use the "best possible" common set of input data leaving the interpretation for the needs of the individual codes to the developers or users of the participating codes.

General Input Data

The data specified for the exercise included such information as population distribution on a geographical grid of varying scale, land use, agricultural production and economic data, and hourly meteorological information for a period of one year. In addition, the participants were given specific values for external exposure shielding and shelter filtering parameters, dry deposition velocity, wash-out coefficient for wet deposition, surface roughness, and breathing rate.

The specifications also included a set of counter-measures, which represented an oversimplification of reality in order to minimize differences in the details of the counter-measures modeling by the various codes.

Source Terms and Cases

There were five source terms specified for the exercise varying in duration and energy of release, time before release, and fractions of the isotope inventory released to the environment. The initial inventory of radioactive nuclides available for release was also specified.

Finally, a series of seven cases to be analyzed were provided (Table 1). Details on the specifications can be found in the Overview and Technical Reports of the exercise to be published by the OECD/NEA and CEC.[2,3] A description of the source terms is given in Table 2. As indicated in Tables 1 and 2 the various combinations of scenarios and source terms selected for the exercise cover a wide range of accident conditions and counter-measures thus providing an opportunity to exercise different features of the codes. The objectives for each calculation can be found in Column 4 of Table 1.

Table 1. Matrix of Calculation Cases

Case*	Case Reference Name	Description	Objective
C1	Single-Phase	Source term ST2. Single-puff release. With economic predictions.	This is the base case with the counter-measures modeled. All materials are released in a single puff.
C2	Long Duration	Source term ST5: same as ST2, but a long duration (24 hours) release. No economic predictions. The source term for this calculation is identical to the source term used in Case 1 except that the release duration is twenty four hours. In the BNL MACCS calculation, this release is sub-divided into four puffs of equal duration. According to the specifications of June 1992, all released materials have to be uniformly distributed among the puffs.	This case is designed to provide data on the sensitivity of consequences to the duration of release.
C3	Single-Phase, No C/M	Source term ST2. Single-puff release. No counter-measures (no evacuation/relocation, no food disposal, and no farmland interdiction). No economic predictions.	This case predicts consequences of a release with no counter-measures. The results are very valuable for comparisons between different codes where implementation of the specified counter-measures could not be accomplished exactly.
C5	Two-Phase+Energy	Source term ST1. Two-puff release. Energy of release is greater than 0 (plume lift-off). No economic predictions.	In this calculation the materials (same fraction of the total inventory as in the base case) are released in two puffs of different duration. The effect of the release energetics is investigated (plume lift-off).
C6	Low Magnitude	Source term ST3. Single-puff low magnitude release. Radius of Fixed (Evacuation) Area is 5 km (note: in the base case scenario, the radius is 10 km). With economic predictions.	In this case the content of aerosols release is reduced by two orders of magnitude (fraction of released noble gases is reduced only by one order of magnitude). In addition, radius of the sheltering zone is reduced by a factor of two.
C7	Three-Phase	Source term ST4. Triple-puff release. No economic predictions.	In this case, the base case release is split into three identical puffs but with different release times.

*Cases numbers are not contiguous which reflects the evolution of the cases matrix over the life of the project.

Table 2. Source Terms

Source Term	Warning Time* (h)	Release Time (h)	Duration of Release (h)	Energy of Release (W)	Xe/Kr	I	Cs	Te	Sr	Ru	La	Ce	Ba
ST1	1.0	2.0	1.0	2.0E+6	1.0	0.101	0.1	0.05	0.0	0.0	0.0	0.0	0.0
		3.0	5.0	2.0E+5	0.0	0.0	0.0	0.05	0.01	0.01	0.001	0.001	0.01
NUREG-1150**													
BHADBCAADEA	0.36	1.03	0.5	1.9E+6	0.99	0.07	0.072	0.0094	0.0024	4.3E-4	1.2E-4	5.5E-4	0.0027
BHADBCAADDA		2.8	6.1	1.7E+5	0.01	0.047	0.0076	0.033	0.011	3.1E-4	0.0013	0.0014	0.0093
ST2	1.0	2.0	1.0	0	1.0	0.101	0.1	0.10	0.01	0.01	0.001	0.001	0.01
ST3	1.0	2.0	1.0	0	0.1	0.00101	0.001	0.001	1.E-4	1.E-4	1.E-5	1.E-5	1.E-4
ST4	1.0	2.0	1.0	0	1.0	0.03333	0.033	0.033	0.0033	0.0033	0.00033	0.00033	0.0033
		3.0	1.0	0	0.0	0.03333	0.033	0.033	0.0033	0.0033	0.00033	0.00033	0.0033
		5.0	1.0	0	0.0	0.03333	0.033	0.033	0.0033	0.0033	0.00033	0.00033	0.0033
ST5	1.0	2.0	24.0	0	1.0	0.101	0.1	0.10	0.01	0.01	0.001	0.001	0.01

*Time in the table is counted from the time of SCRAM according to the MACCS convention

**This is a two-puff release corresponding to the V-sequence (by-pass) in the NUREG-1150 Study (NUREG/CR-4551) for the Surry-1 nuclear power plant (three-loop PWR). This accident sequence is initiated by a failure of the check valves separating the RCS and the Low Pressure Injection System (LPSI). A release into the environment through the auxiliary building develops following a subsequent failure of the LPSI piping. This source term with some modifications served as a prototype for the International Intercomparison Exercise

Counter-Measures Specifications

The exercise specifications included the following counter-measure scenarios:

a) full circle evacuation from a 10 (or 5) km circle,
b) timed sheltering followed by instantaneous evacuation,
c) exposure criterion for relocation and return of relocatees, and
d) crop bans/crop farmland interdiction based on the specific crop contamination levels.

It should be noted that the last set of specifications—crop bans/farmland interdiction criteria—could not be designed in such a way as to fully accommodate all of the particular input data needs of all codes participating in the exercise.

Calculated Results Requested for Comparison

Three major sets of consequence measures were subject to inter-code comparison: dose predictions, health effects, and economic losses. Some intermediate measures, such as the air and land contamination were also compared. The specific consequences requested for comparisons were collective dose, health effects (e.g., numbers of early fatalities and latent cancer fatalities), effect of counter-measures on people (e.g. total number of people relocated), effect of counter-measures on agriculture (e.g., area of interdicted farmland), and economic effects (e.g., cost of food bans). The results requested from all participants included Complementary Cumulative Distribution Functions (CCDFs) for various effects, as well selected parameters (e.g., percentiles and mean values).

INTER-CODE COMPARISON

Predictions of major measures (end-points) for Case 1 (base case) are presented in Fig. 1. This format of comparison provides an overview of the results across all the important end-points starting from doses to health effects to the results of counter-measures for each case. The observed differences are attributed to differences in modeling and weather sampling techniques employed in the participating codes. Comparisons for three major measures across all cases are presented below. This format is advantageous in the evaluation of the sensitivity of each particular measure to the calculation scenario and source term characteristics.

Doses and Health Consequences

The results predicted for the collective dose calculations for Case 1 show a spread of about a factor of 2 in the mean values. The spread in the 99th percentile values was approximately twice as large resulting from meteorological sampling variations (Fig. 2). Spreads in these results for other cases are of similar magnitude. The large variation observed for the predictions of early health effects was caused by the threshold-type models used in the codes which made the results very sensitive to variations in meteorological samplings. The spread in the predicted latent effects in general reflected that observed in the collective dose predictions.

Economic Consequences

The spread in prediction of the number of relocated people (Fig. 3) was about a factor of four for the mean values and about an order of magnitude for the 99th percentile. The spread is attributed to differences in the meteorological sampling schemes employed by the different codes as well as in the atmospheric dispersion models.

Summary of Codes Inter-Comparison

The magnitude of differences in the predictions of expectation values of various measures (expressed as a ratio of a group's maximum value to the group's minimum value) was generally found to be below a factor of five. The observed differences have been attributed to differences in modeling and weather sampling techniques used in the different codes participating in the exercise.

Figure 1. Codes Inter-Comparison (Mean Values). Case 1: Single Phase, Base Case

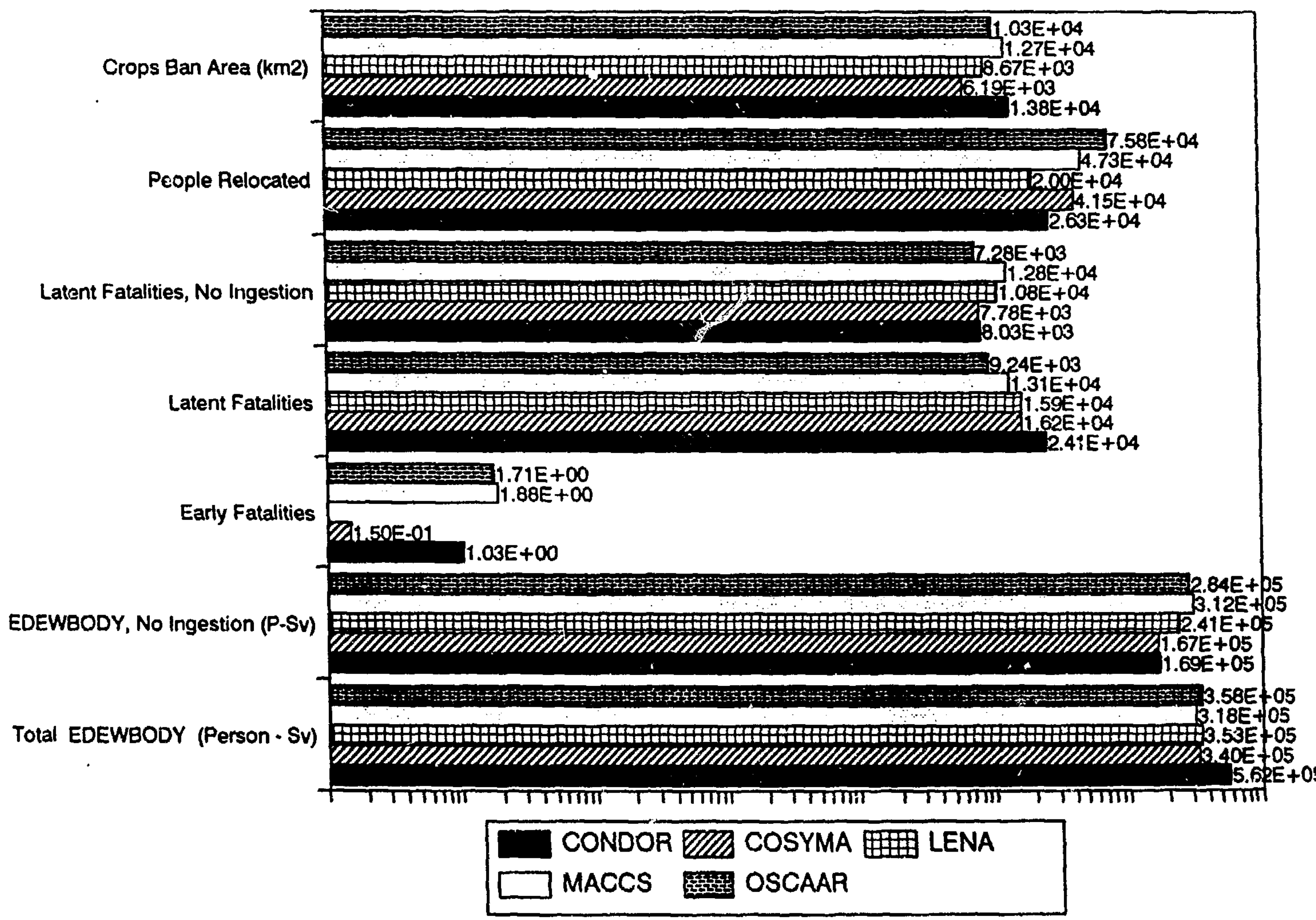


Figure 2. Inter-Code Comparison: Prediction of Total CEDEC

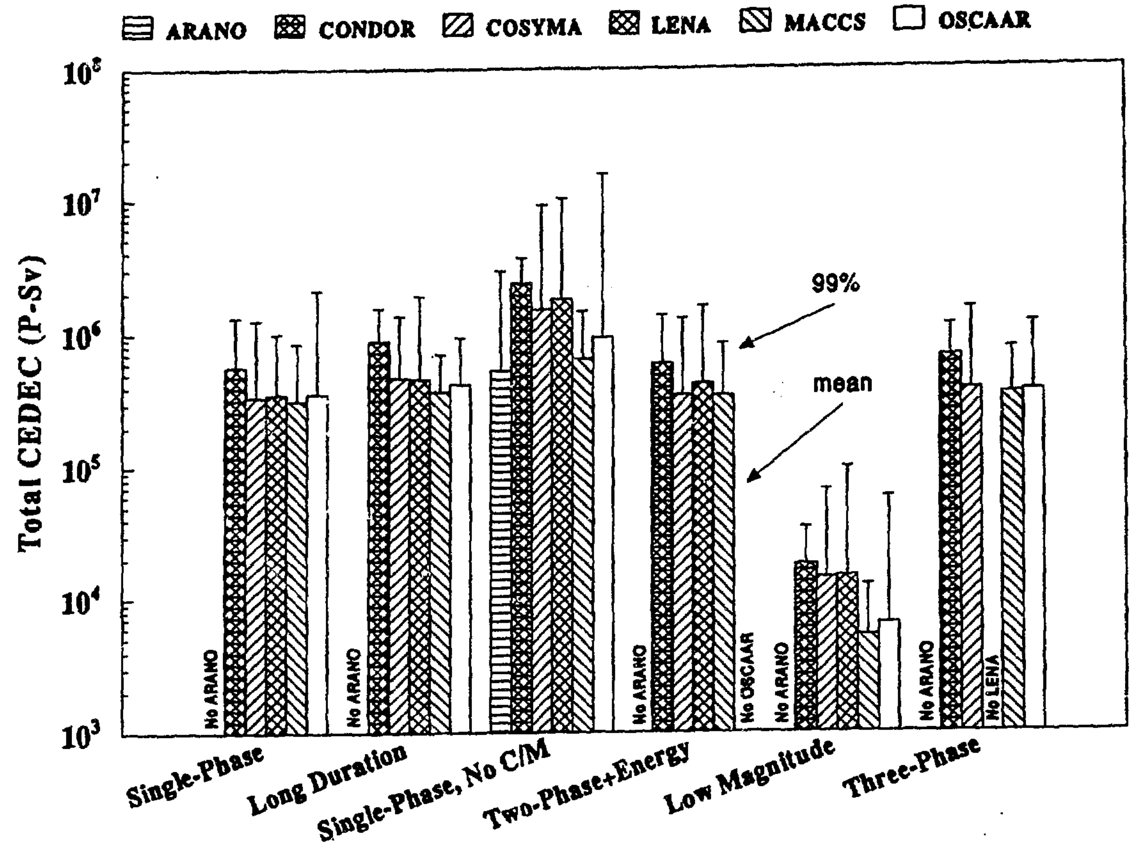
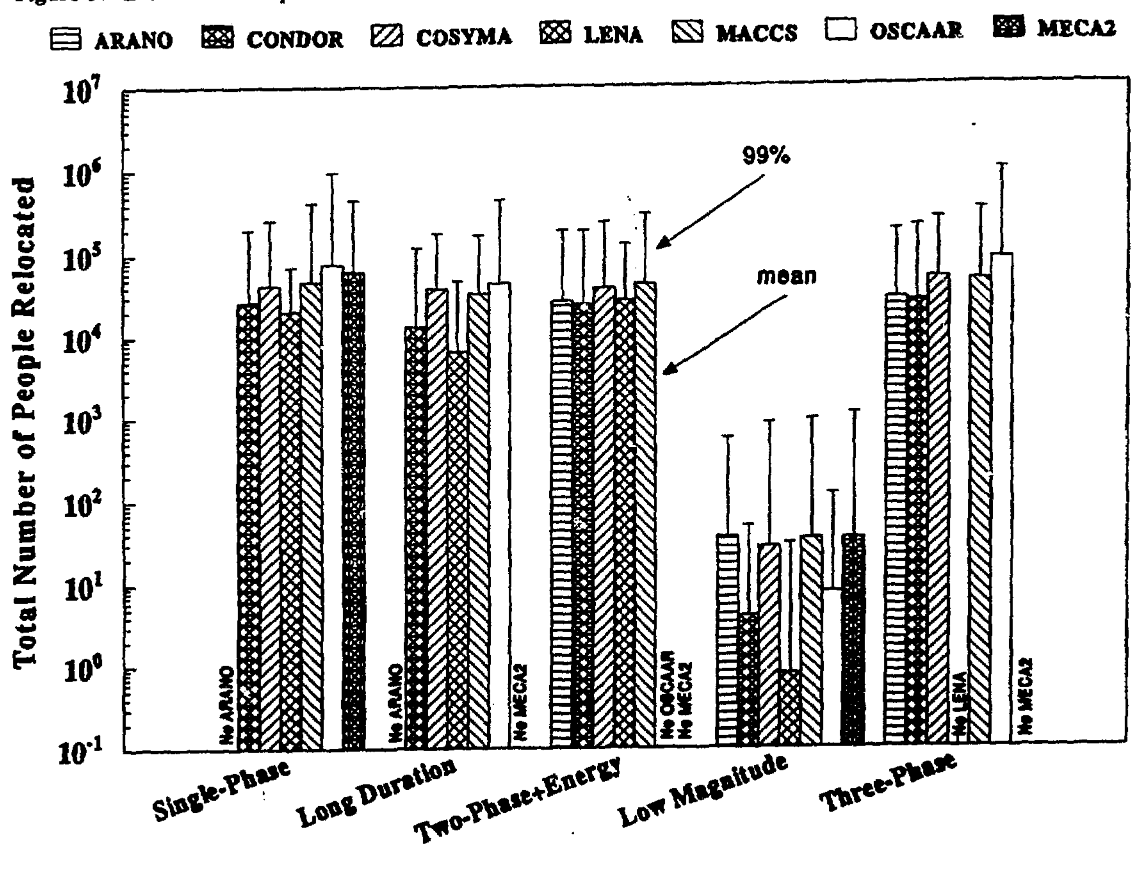


Figure 3. Inter-Code Comparison: Prediction of Total Number of People Relocated



MACCS USERS GROUP COMPARISON

The objectives[4] established for the MACCS Users Group inter-comparison effort included the following:

- demonstrate the **"user-friendliness" of MACCS** enabling the users from different countries to interpret specifications and use them to prepare the input data as well as test the **code's flexibility** in accepting generic specifications,
- screen out and eliminate possible inconsistencies in the input data intended for further use in the calculations performed for the inter-code comparisons, thus providing quality assurance,
- analyze results and explain reasons for differences between the four calculation results, evaluate the sensitivity of results to choices users make in the course of input preparation,
- provide a forum for discussion of users experience in working with the MACCS code and using it's documentation, and
- identify areas for code improvement.

Note that out of the seven cases specified for the calculations, Case 7 was not calculated by MACCS since the code does not have an option for food disposal and farmland interdiction. Counter-measures in the code are based on the predicted **food contamination level.**

Before discussing the results of the comparison for different cases, results obtained for Case 1 (base case, mean values) are illustrated in Fig. 4. The differences in the results are mainly attributed to some differences in grids and population distribution which was extracted from the demographic data separately by each participant. The major differences in the dose predictions (specifically, ingestion pathway dose) are due to variations in interpretation of the agricultural and food dose pathway related data which was specified for the exercise.

Doses and Health Consequences

The predictions of total collective dose are very close for all the calculations with variations attributed to the differences in grids, population distribution, and meteorological data. The major differences in the predicted total societal doses are caused by the ingestion pathway dose predictions, which can be ascertained by comparing Figs. 5 and 6 which show the doses predicted in all six cases. This conclusion is illustrated clearly by Fig. 6 which displays the total doses calculated without the ingestion dose pathway: agreement between the four calculation results is excellent.

Note that in all cases the differences in the ingestion dose predictions did not significantly affect the total dose results. The exception is Case 3 where **no counter-measures were modeled** and the ingestion pathway was an important contributor to the total dose. The differences in the dose predictions are mainly due to differences in the mapping of the agricultural production and in the dose criteria for crop disposal and farmland interdiction. Other causes of differences between predictions are the variations in the values of retention and transfer factors for different crops used by the participants.

Differences in predictions of the number of **early health effects** (early fatalities and hypothyroidism morbidities) are attributed to some variations in the meteorological input files and weather sampling, differences in grids and population distributions combined with the impact of the threshold-type models used for predicting the early health effects. It has to be noted that the differences are greatest in the CCDF's higher percentile regions which is caused by an increased sensitivity of the results to the variations in the weather sampling.

The **number of fatal cancers** predicted **without the ingestion pathway dose** showed very small differences between the four MACCS Users Group results for all six cases. As expected, the differences in the total number of fatal cancers predicted by taking into account the ingestion pathway doses are largest for Case 3 (no counter-measures) resulting from the differences in the ingestion dose predictions.

Similar to the early fatalities predictions, the predictions of **conditional individual risk of latent and early fatalities** as a function of distance agree well with the differences between results increasing at farther distances from the plant site where the effects of differences in the weather sampling become more pronounced.

Figure 4. MACCS Inter-Comparison (Mean Values). Case 1: Single-Phase, Base Case

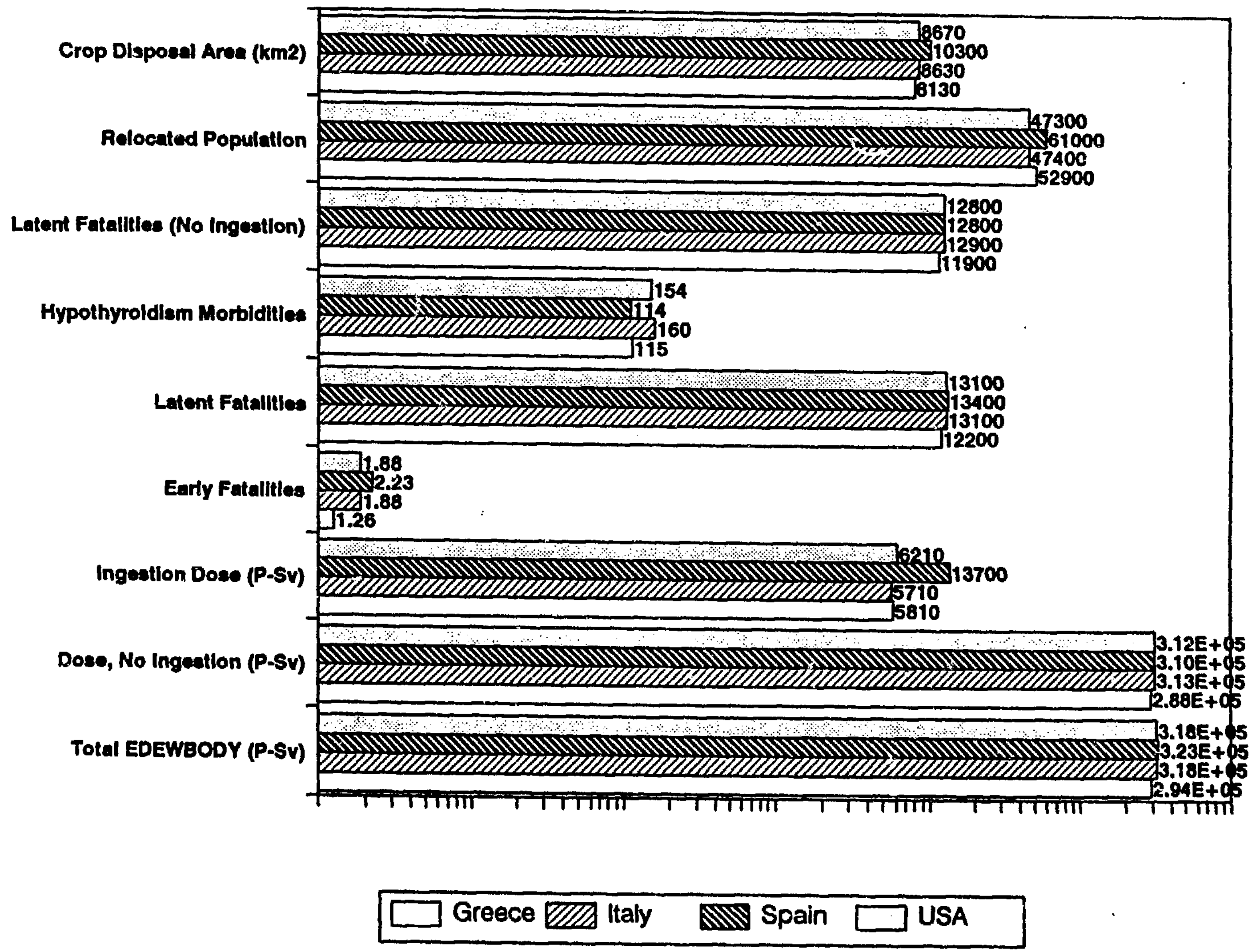


Figure 5. MACCS Inter-Comparison: Prediction of Total CEDEC

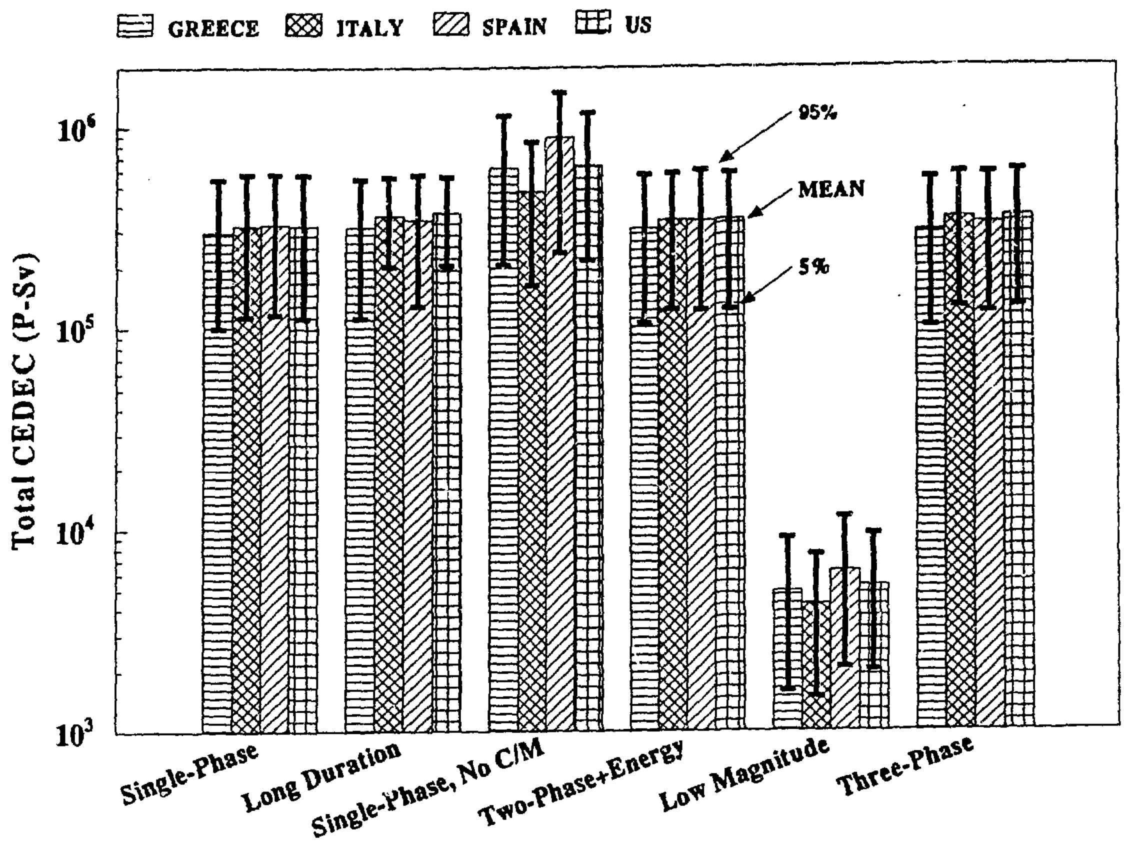


Figure 6. MACCS Inter-Comparison: Prediction of Total CEDEC Excluding Ingestion

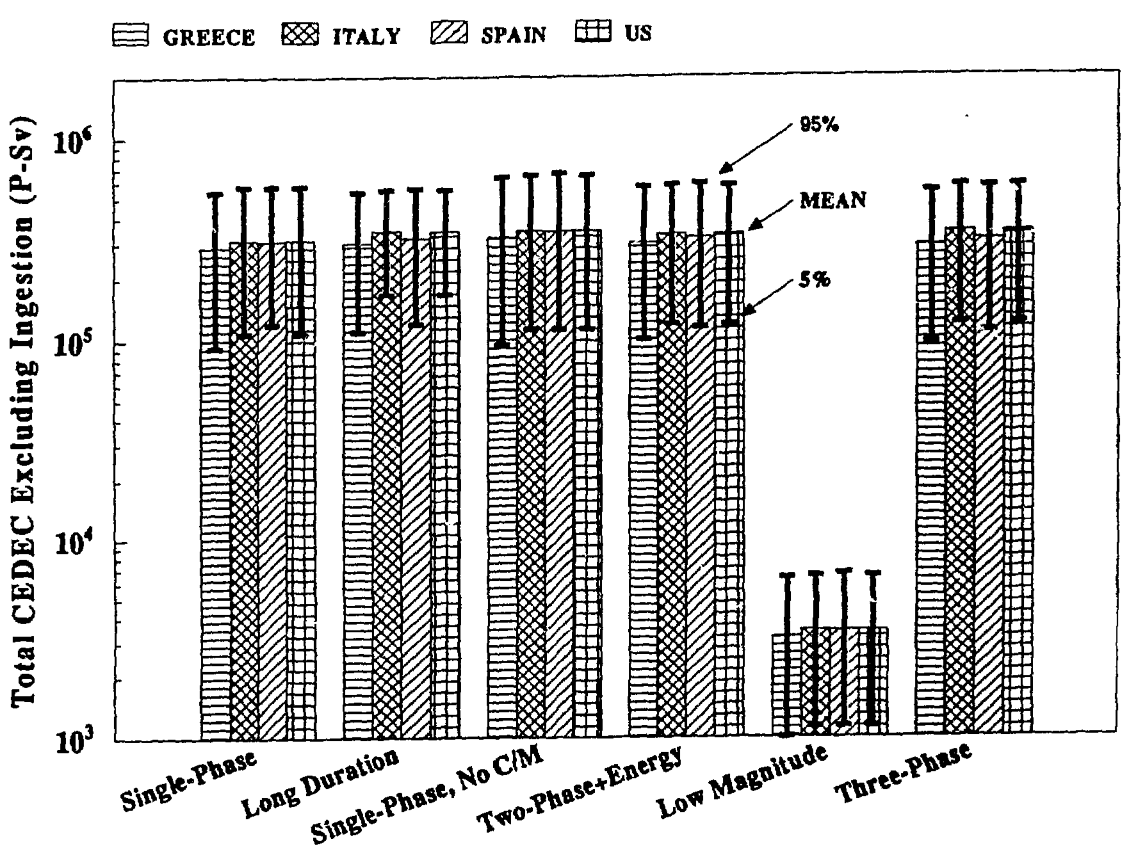
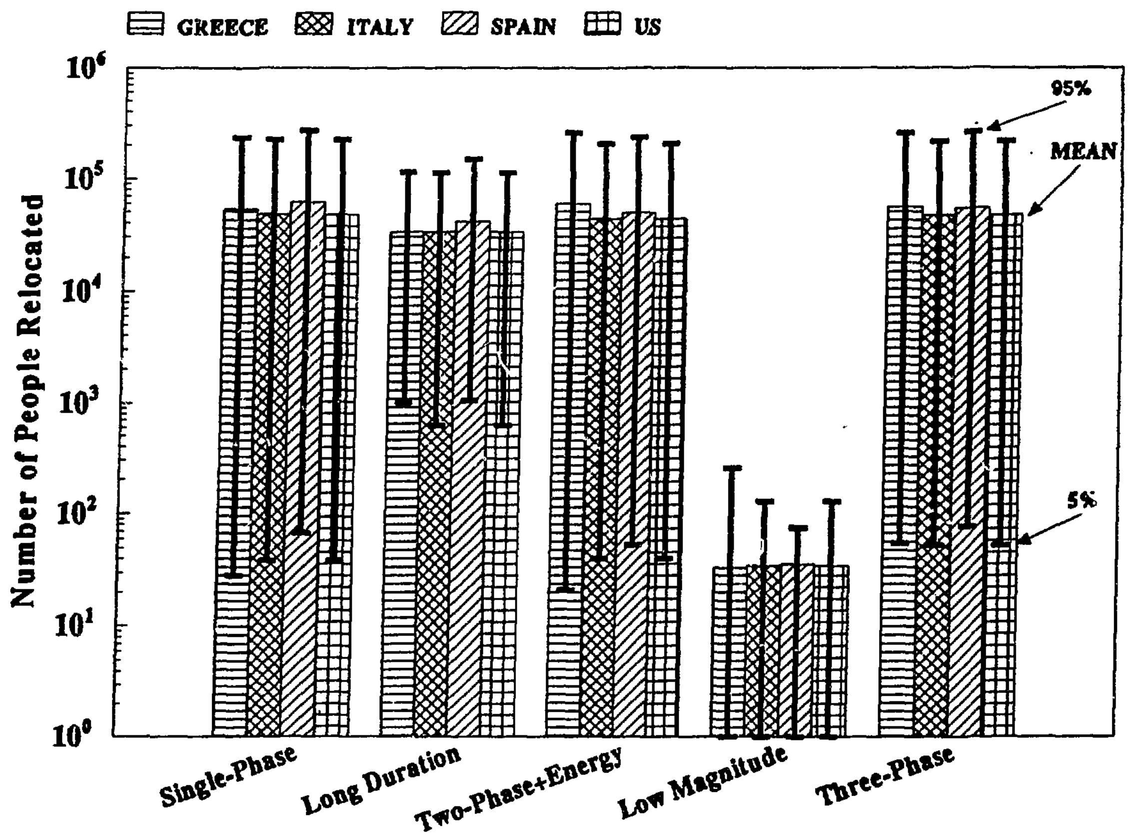


Figure 7. MACCS Inter-Comparison: Prediction of Number of People Relocated



Economic Consequences

The predictions of the total number of relocated people for five cases which modeled counter-measures are shown in Fig. 7. The 5th percentile values predicted for the low magnitude release (Case 6) indicate a significant number of weather sequences requiring no relocation (CCDFs show that the median value of number of relocatees is also zero). The differences between the results are attributed to differences in the weather sampling, grids, and dispersion model options.

The differences in predictions of total costs related to people relocation are, to a large extent, a reflection of differences in predictions of the number of people relocated since the variations in the unitary relocation costs used in the calculations are not significant. Note that these costs include the values of interdicted land and capital investment and constitute the bulk of population related costs; the daily evacuation costs which depend on the daily cost of evacuation/relocation are insignificant in comparison.

Differences in predictions of costs of crop disposal are mainly due to differences in the mapping of agricultural production (homogenized versus distributed) and in the crop banning criteria. Sensitivity calculations for Case 1 (Single-Phase Release) also showed an influence of other factors (meteorological data and weather sampling) on the differences in predictions.

Summary of MACCS Inter-Comparison

In general, good agreement between the results produced by the four MACCS Users Group participants was achieved, with the exception of the results related to the ingestion pathway dose predictions. The main reason for the differences in the latter results is attributed to variation in approaches to implementation of the specifications for the agricultural production and counter-measures criteria provided for the exercise. Significantly smaller differences between predictions of other consequences can be explained by differences in weather sampling, grids, rain distance intervals, dispersion model options, and population distributions.

CONCLUSION

An international comparison of PCA codes provides a forum for researchers specializing in accident consequence analysis to discuss their technical position on various aspects of dose, health, and economic consequence modeling. The exercise also provides an opportunity to compare the results produced by different codes/countries and identify and explain differences in predictions. Finally, the exercise provides a mechanism for international cooperation in accident consequence modeling.[4]

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