

SIMULATING NUCLEAR-WASTE DISPOSAL AND STORAGE

As regards disposal and storage of nuclear waste, as in other areas, simulation complements experimentation. More than in other areas of concern, however, owing to the time scale involved, simulation can substitute for experimentation. Its function? To facilitate the search for the decisive parameters in the evolution of a site, of materials and packages, and finally the evolution of radiation doses that must be contained as long as they could have an effect on man.



A geologist and a computer graphics operator working on a model of the Meuse/Haute-Marne underground laboratory for research on nuclear-waste disposal, on the Bure site itself.

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P. Demall/Andra

A predictive approach

Safety or performance assessments of a nuclear-waste disposal or storage site⁽¹⁾ essentially consist in predicting the evolution over time of this site, its infrastructural materials and finally of the waste packages.⁽¹⁾ The ultimate purpose of this prediction, in the disposal case, is to determine **radionuclide** doses⁽²⁾ and the associated arrival times into the **biosphere**, and for storage it is to predict the state of integrity of infrastructure materials and packages, with a view to their eventual recovery by man.

The time scales involved vary from a few decades to several thousand years – making direct experiment difficult. The role of **simulation** thus is to complement or substitute for experimentation, to shed light on the range of possible situations, to facilitate the search for controlling **parameters**, for example by carrying out *sensitivity studies* in which many physical parameters and geo-

metric configurations are evaluated (see Box A, *What is a numerical simulation?*). Simulation allows operational tools to be developed, reflecting the knowledge gained and validated at a given time.

Physical–chemical mechanisms

The physical–chemical mechanisms governing the behavior of a disposal or storage site are many, and complex. For instance, consider a normal evolution scenario for a geological disposal site. During the rock-excavation phase, i.e. over several decades, underground flows are modified. Rock close to shafts and tunnels becomes “desaturated” in water and its mechanical behavior is disturbed. After the site is closed, heat released by the waste packages raises the temperature of the disposal area. The rock, then the engineered barrier and backfill materials become resaturated with water. Mechanical behavior of all these materials moves towards

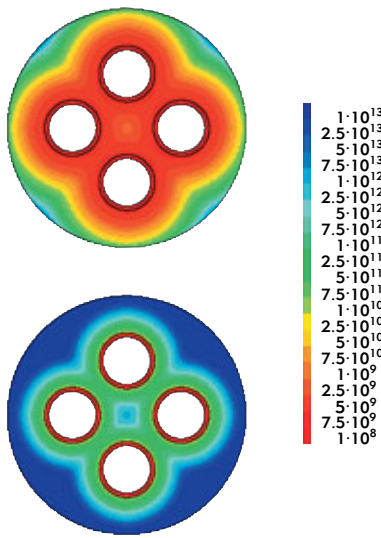
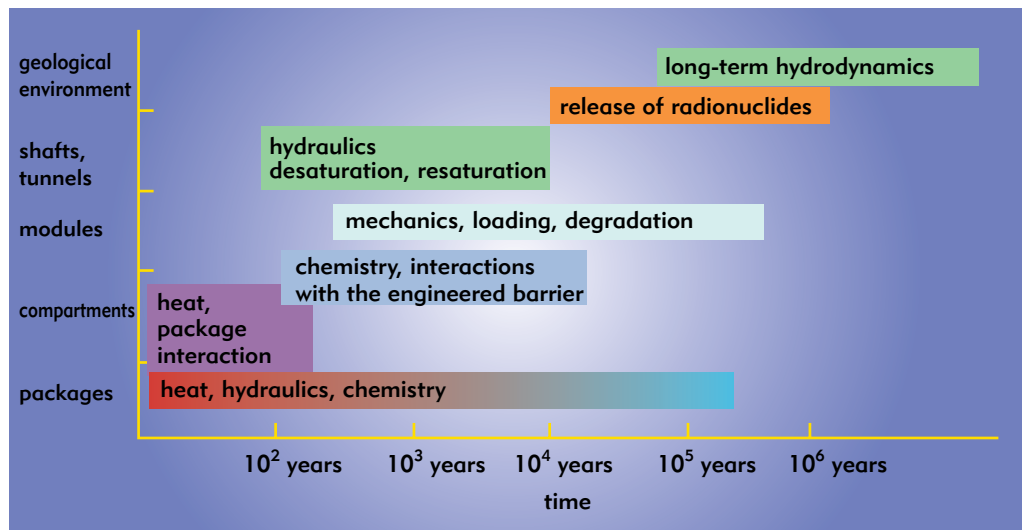
an equilibrium state. Water corrodes the packages and becomes laden with radionuclides. These then migrate, initially through the materials and then through the rock mass, tending to the surface. This migration is constrained by chemical interactions of the radionuclides with the materials and rock. This scenario stems from the phenomenological analysis of disposal situations (APSS)

(1) In this respect, see *Clefs CEA* No. 46, Spring 2002. *Storage*, which is different from *disposal* by its temporary (albeit possibly long-term) nature, may be effected in a *surface* or *subsurface* (at depths of a few tens of meters in the natural environment) facility. The waste intended for disposal is conditioned in the form of *packages* which may be put into groups inside *compartments*, which in turn may be grouped in *modules* distributed within the *geological environment*.

(2) See Box in the article *Simulation of intervention in a hostile environment*.

Figure 1. Diagram showing the phenomenological analysis of disposal situations (APSS) by Andra showing the dominant phenomena to be described in space and time.

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CEA/DEN/DED
Figure 2. Comparison, in the form of nickel-59 concentration maps at 1 million years, of two concepts of compacted-waste packages without (top) and with complementary packaging (bottom).

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carried out by Andra (Agence nationale pour la gestion des déchets radioactifs - French National Agency for Radioactive Waste Management) during recent years. This may be shown in diagrammatic form indicating, for each spatial order of scale of the disposal facility (packages, compartments, modules, geological environment)⁽¹⁾ and for each time scale, the dominant physical-chemical mechanisms involved (Figure 1).

As regards in particular surface or subsurface storage,⁽¹⁾ one of the major problems encountered is that of dissipation of heat released by the packages. This must be evacuated from the facility, by forced convection for example, to preclude any critical rise in temperature in the infrastructure materials that could lead to mechanical damage. The aim is to conserve the integrity of materials

and packages with a view to future recovery. A distinction can be made between three spatial orders of scale, for the simulation of disposal. On the scale of the *package*, the aim is to predict corrosion of the package by water at the site: corrosion of the container, degradation of the matrix (glass, cement, etc.), and subsequent release of radionuclides (Figure 2). Such knowledge is taken up in operational models to be used thereafter, coupled with models for the behavior of compartments and the geological environment. On the scale of the disposal *compartment*, all gradients (thermal, chemical, etc.) are significant. The compartment is thus the site where major couplings take place, be they thermal-hydro-mechanical or thermo-hydro-chemical. While some processes are linear, e.g. radionuclide transport through shear diffusion, coupled processes are as a rule highly non-linear, as for instance radionuclide transport in the presence of precipitation or dissolving. These require specific **numerical methods**, since all equations describing such processes must be solved simultaneously. This coupling can be used to assess package performance in a given environment and will form the source term for the third domain: the geological environment (Figure 3).

In the *geological environment*, gradients become weak, and radionuclide transport becomes the sole dominant process. While transport mechanisms (through convection, diffusion or dispersion) are simple as far as simulation is concerned, the (multi-layer) topology of the environment, its extent (several kilometers, corresponding to a million **mesh cells** for the simulator), and contrasting properties within it (alternations of permeable and semi-permeable strata) make the simulation of radionuclide migration in the geological environment over several million years an exercise that is anything but straightforward (see Figure 4).

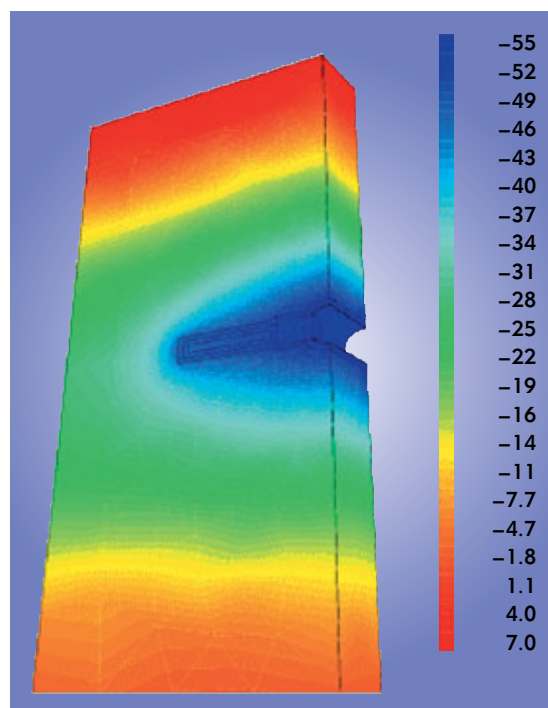


Figure 3. Study of the hydraulic pressure field (in meters of water) around a waste-package disposal compartment.

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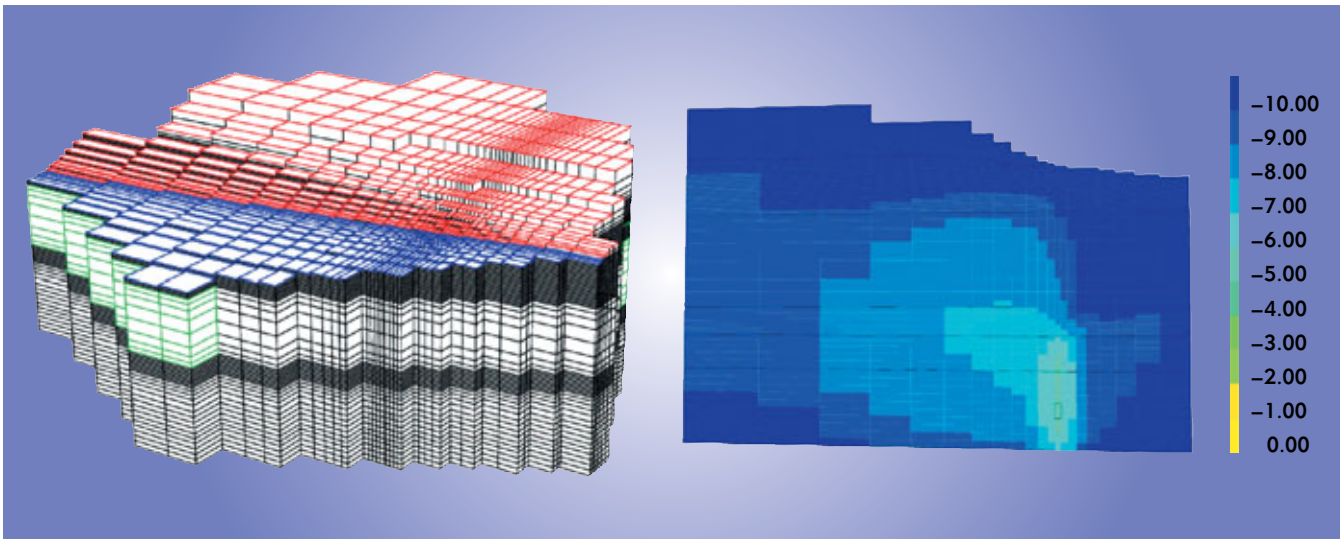


Figure 4. Three-dimensional mesh for the Bure experimental site (Meuse/Haute-Marne, North-Eastern France) and isovalues of iodine-129 concentration (in mol/m³) on a logarithmic scale.

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clides, etc., while the **modeling** environment includes the 3D geometric modeler (set of basic geometric shapes that may be assembled to describe a package, a compartment or site), mesh and visualization tools, and data-acquisition tools, and functions for coupling and distributing components across several **processors** (see Box B, **Computational resources for high-performance numerical simulation**). Finally, the ensemble of coupling schemas and calculation methodologies is validated on reference situations for disposal and storage.

Concurrently with the development of Alliances, the CEA and Andra teams are involved in national collaborative efforts in the field of numerical simulation through the Momas research group, and in geochemistry through the Geochemistry Transport Pole. The two organizations' avowed aim to get the Alliances simulation approach adopted at European level should result in a proposal for an integrated project for the 6th Framework Program for research, technological development and demonstration (FP6).

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The Alliances simulation tool

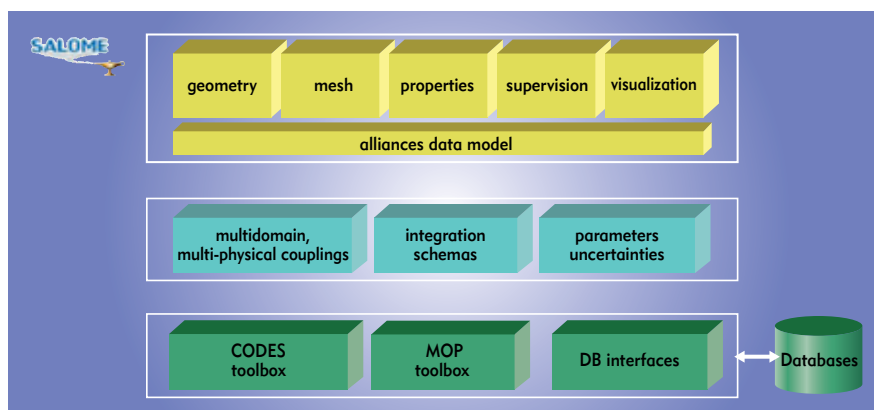
Simulation of the evolution of a disposal or storage site is inherently multi-physical and multi-disciplinary. To meet this requirement, the Alliances project (*Atelier Logiciel pour l'Intégration, l'ANalyse et la Conception des Entreposages et Stockages* – Software Workshop for Integration, Analysis and Design of Storage and Disposal Facilities) was launched by CEA and Andra in June 2001. Its purpose? To allow performance and safety studies to be carried out, facilitate research and development initiatives on numerical schemas and physical models, and draw on knowledge gained in various departments at CEA and Andra, and other partners (universities, outside service providers, etc.). Choices were made in three areas, giving the project its shape. The first choice was *joint development*. A joint CEA–Andra team was set to work to share development costs and facilitate bringing in all and any future users for the drawing up of specifications and validation of the platform. The second choice

was to go for *use of numerical components*. Advances in **software engineering** (see Box E, **Advances in software engineering**) and the growth in computational resources mean it is now possible to consider reuse of components developed independently, thus taking advantage of CEA's experience in this area. Furthermore, such reuse makes it possible to choose the component best suited for the description of a given situation: thus the Chess software, developed by the École des Mines and others, was chosen as the geochemistry engine for the platform. Finally, the Alliances software environment is derived from the Salomé (*Simulation par Architecture LOGicielle à Méthodologie d'Évolution* - Simulation by Software Architecture with Evolution Methodology) infrastructure, enabling the team to focus on aspects specific to the project such as building up a model of user data and integrating components (Figure 5).

A consistent software environment

Alliances will thus provide users with a consistent software environment comprising all tools required for the analysis of a disposal or storage concept. *Numerical components* describe the behavior of packages, underground flows, migration of radionu-

Figure 5. General architecture of the Alliances simulation tool.



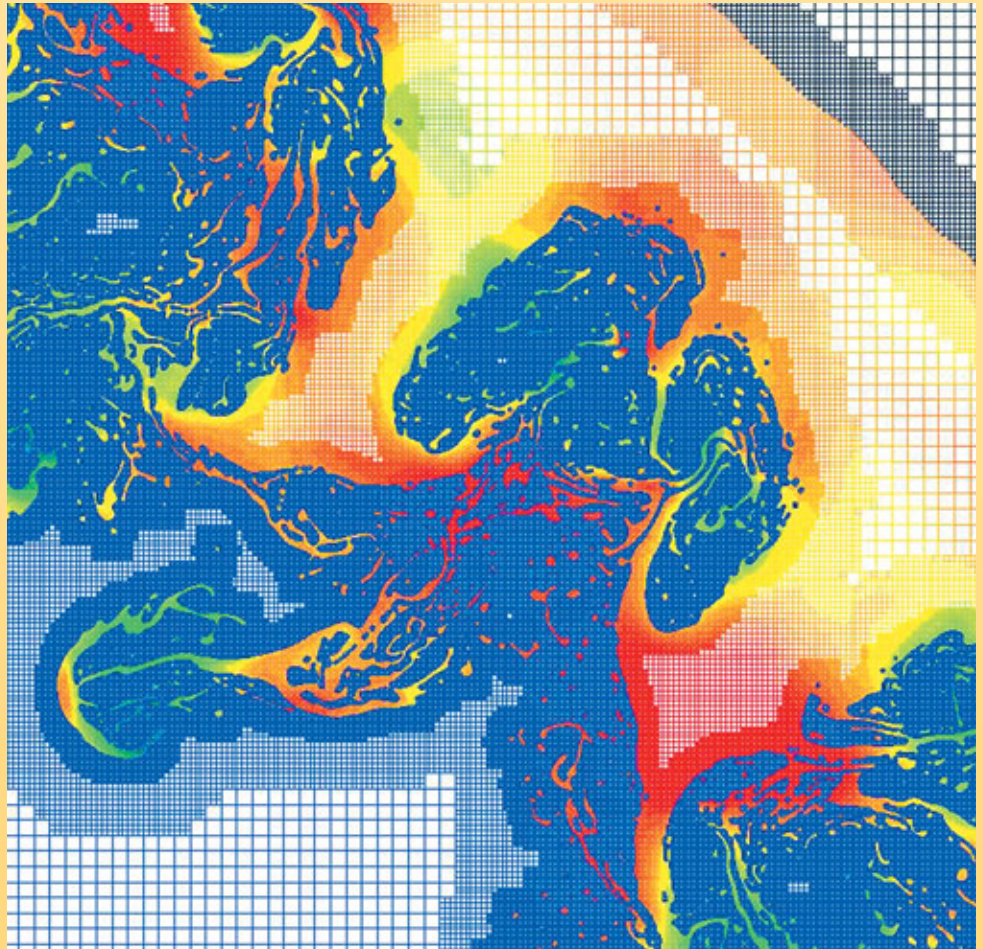
Numerical simulation consists in reproducing, through computation, a system's operation, described at a prior stage by an ensemble of **models**. It relies on specific mathematical and computational methods. The main stages involved in carrying out an investigation by means of numerical simulation are practices common to many sectors of research and industry, in particular nuclear engineering, aerospace or automotive.

At every point of the "object" considered, a number of physical quantities (velocity, temperature...) describe the state and evolution of the system being investigated. These are not independent, being linked and governed by **equations**, generally **partial differential** equations. These equations are the expression in mathematical terms of the physical laws modeling the object's behavior. Simulating the latter's state is to determine – at every point, ideally – the numerical values for its parameters. As there is an infinite number of points, and thus an infinite number of values to be calculated, this goal is unattainable (except in some very special cases, where the initial equations may be solved by analytical formulae). A natural approximation hence consists in considering only a finite number of points. The parameter values to be computed are thus finite in number, and the operations required become manageable, thanks to the computer. The actual number of points processed will depend, of course, on computational power: the greater the number, the better the object's description will ultimately be. The basis of parameter computation, as of numerical simulation, is thus the reduction of the infinite to the finite: **discretization**.

How exactly does one operate, starting from the model's mathematical equations? Two methods are very commonly used, being representative, respectively, of **deterministic computation** methods, resolving the equations governing the processes investigated after discretization of the variables, and methods of **statistical** or **probabilistic calculus**.

The principle of the former, known as the **finite-volume method**, dates from before the time of computer utilization. Each of the object's points is simply assimilated to a small elementary volume (a cube, for instance), hence the *finite-volume* tag. Plasma is thus considered as a set or lattice of contiguous volumes, which, by analogy to the makeup of netting, will be referred to as a **mesh**. The parameters for the object's state are now defined in each mesh cell. For each one of these, by reformulating the model's mathematical equations in terms of volume averages, it will then be possible to build up *algebraic relations* between the parameters for one cell and those of its neighbors. In total, there will be as many relations as there are unknown parameters, and it will be up to the computer to resolve the *system* of relations obtained. For that purpose, it will be necessary to turn to the techniques of **numerical analysis**, and to program specific **algorithms**.

The rising power of computers has allowed an increasing fineness of discretization, making it possible to go from a few tens of cells in the 1960s to several tens of thousands in the 1980s, through to millions in the 1990s, and up to some ten billion cells nowadays (Tera machine at CEA's Military Applications Division), a figure that should increase tenfold by the end of the decade.



Example of an image from a 2D simulation of instabilities, carried out with CEA's Tera supercomputer. Computation involved adaptive meshing, featuring finer resolution in the areas where processes are at their most complex.

A refinement of meshing, **adaptive remeshing**, consists in adjusting cell size according to conditions, for example by making them smaller and more densely packed at the interfaces between two environments, where physical processes are most complex, or where variations are greatest.

The finite-volume method can be applied to highly diverse physical and mathematical situations. It allows any shape of mesh cell (cube, hexahedron, tetrahedron...), and the mesh may be altered in the course of computation, according to geometric or physical criteria. Finally, it is easy to implement in the context of **parallel computers** (see Box B, **Computational resources for high-performance numerical computation**), as the mesh may be subjected to partitioning for the purposes of computation on this type of machine (example: Figure B).

Also included in this same group are the **finite-difference method**, a special case of the finite-volume method where cell walls are orthogonal, and the **finite-element method**, where a variety of cell types may be juxtaposed.

The second major method, the so-called **Monte Carlo** method, is particularly suited to the simulation of *particle transport*, for example of neutrons or photons in a **plasma** (see *Simulations in particle physics*). This kind of transport is in fact characterized by a succession of stages, where each particle may be subject to a variety of events (diffusion, absorption, emission...) that are possible *a priori*. Elementary probabilities for each of these events are known individually, for each particle.

It is then a natural move to assimilate a point in the plasma to a particle. A set of particles, finite in number, will form a representative sample of the infinity of particles in the plasma, as for a statistical survey. From one stage to the next, the sample's evolution will be determined by random draws (hence the method's name). The effectiveness of the method, implemented in Los Alamos as early as the 1940s, is of course dependent on the statistical quality of the random draws. There are, for just this purpose, *random-number* methods available, well suited to computer processing.

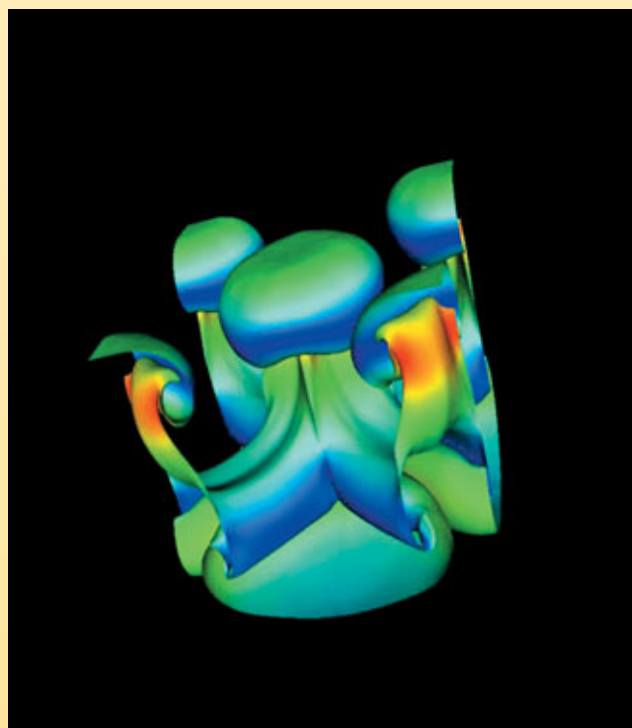
How does a numerical simulation proceed?

Reference is often made to *numerical experiments*, to emphasize the analogy between performing a numerical simulation and carrying out a physical experiment.

In short, the latter makes use of an experimental setup, configured in accordance with initial conditions (for temperature, pressure...) and control parameters (duration of the experiment, of measurements...). In the course of the experiment, the setup yields measurement points, which are recorded. These records are then analyzed and interpreted.

In a numerical simulation, the experimental setup consists in an ensemble of computational programs, run on computers. The **computation codes**, or **software** programs, are the expression, via numerical algorithms, of the mathematical formulations of the physical models being investigated. Prior to computation, and subsequent to it, *environment software* programs manage a number of complex operations for the preparation of computations and analysis of the results.

The initial data for the simulation will comprise, first of all, the delineation of the computation domain – on the basis of an approximate representation of the geometric shapes (produced by means of drafting and CAD [computer-assisted design] software) –, fol-



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3D simulation carried out with the Tera supercomputer, set up at the end of 2001 at CEA's DAM-Île de France Center, at Bruyères-le-Châtel (Essonne département).

Finite-volume and Monte Carlo methods have been, and still are, the occasion for many mathematical investigations. These studies are devoted, in particular, to narrowing down these methods' convergence, i.e. the manner in which approximation precision varies with cell or particle number. This issue arises naturally, when confronting results from numerical simulation to experimental findings.

lowed by discretization of this computation domain over a mesh, as well as the values for the physical parameters over that mesh, and the control parameters to ensure proper running of the programs... All these data (produced and managed by the environment software programs) will be taken up and verified by the codes. The actual results from the computations, i.e. the numerical values for the physical parameters, will be saved on the fly. In fact, a specific protocol will structure the computer-generated information, to form it into a numerical database.

A complete protocol organizes the electronic exchange of required information (dimensions, in particular) in accordance with predefined formats: modeler,⁽¹⁾ mesher,⁽²⁾ mesh partitioner, com-

(1) The modeler is a tool enabling the generation and manipulation of points, curves and surfaces, for the purposes, for example, of mesh generation.

(2) The geometric shapes of a mesh are described by sets of points connected by curves and surfaces (Bézier curves and surfaces, for instance), representing its boundaries.

putation codes, visualization and analysis software programs. *Sensitivity* studies regarding the results (sensitivity to meshes and models) form part of the numerical “experiments.”

On completion of computation (numerical resolution of the equations describing the physical processes occurring in each cell), analysis of the results by specialists will rely on use of the numerical database. This will involve a number of stages: selective extraction of data (according to the physical parameter of interest) and visualization, and data extraction and transfer for the purposes of computing and visualizing diagnostics.

This parallel between performing a computation case for a numerical experiment and carrying out a physical experiment does not end there: the numerical results will be compared to the experimental findings. This comparative analysis, carried out on the

basis of standardized quantitative criteria, will make demands on both the experience and skill of engineers, physicists, and mathematicians. Its will result in further improvements to physical models and simulation software programs.

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The example of a thermalhydraulics computation

Implementation of a numerical simulation protocol may be illustrated by the work carried out by the team developing the **thermalhydraulics** computation software Trio U. This work was carried out in the context of a study conducted in collaboration with the French Radiological Protection and Nuclear Safety Institute (IRSN: Institut de radioprotection et de sûreté nucléaire). The aim was to obtain very accurate data to provide engineers with wall heat-stress values for the components of a pressurized-water reactor in case of a major accident involving turbulent natural circulation of hot gases. This investigation requires simultaneous modeling of large-scale “system” effects and of small-scale **turbulent** processes (see Box F, *Modeling and simulation of turbulent flows*).

This begins with specification of the overall computation model (Figure A), followed by production of the CAD model and corresponding mesh with commercial software programs (Figure B). Meshes of over five million cells require use of powerful graphics stations. In this example, the mesh for a steam generator (Figures C and D) has been partitioned to parcel out computation over eight processors on one of CEA’s parallel computers: each color stands for a zone assigned to a specific processor. The computations, whose boundary conditions are provided by way of a “system” computation (Icare–Cathare), yield results which it is up to the specialists to interpret. In this case, visualization on graphics stations of the instantaneous values of the velocity field show the impact of a hot plume on the steam generator’s tube-plate (section of the velocity field, at left on Figure E), and instantaneous temperature in the water box (at right).

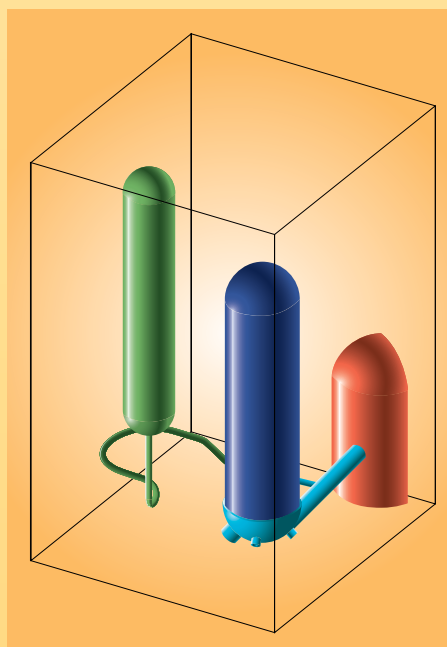


Figure A. Overall computation domain, including part of the reactor vessel (shown in red), the outlet pipe (hot leg, in light blue), steam generator (dark blue), and pressurizer (green).

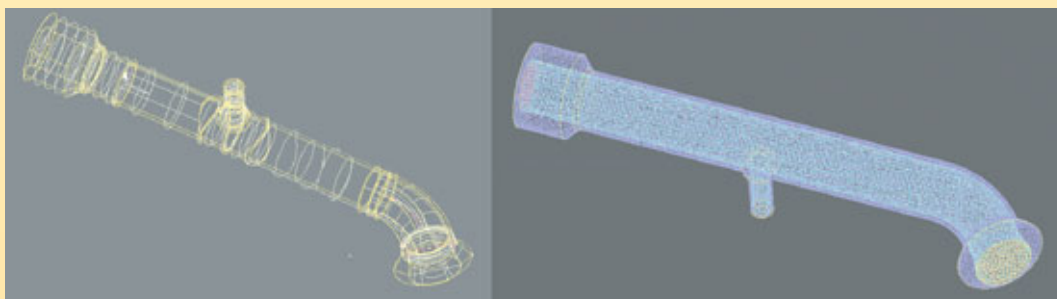
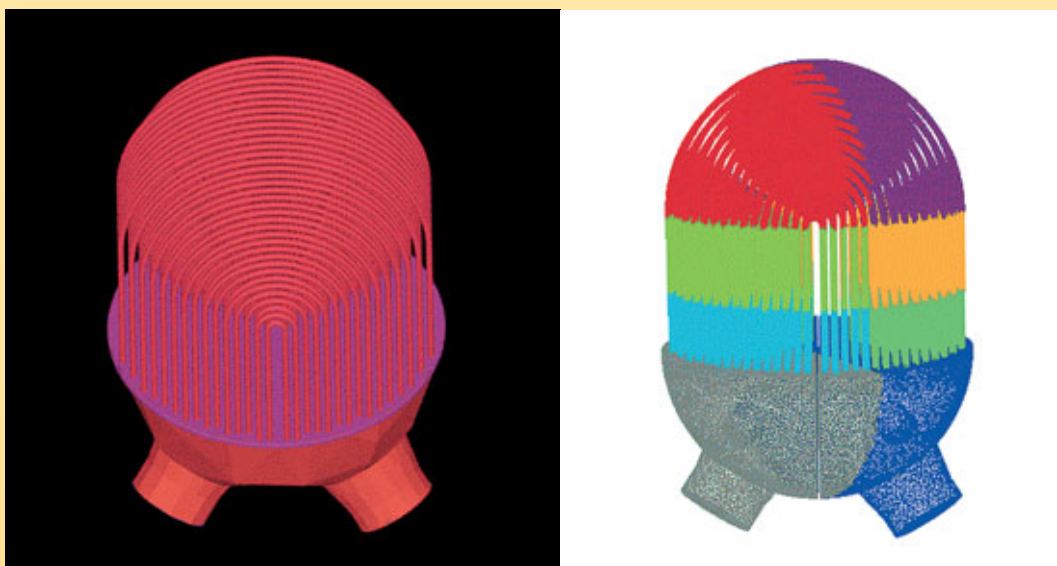


Figure B. CAD model of the hot leg of the reactor vessel outlet (left) and unstructured mesh for it (right).



Figures C and D.

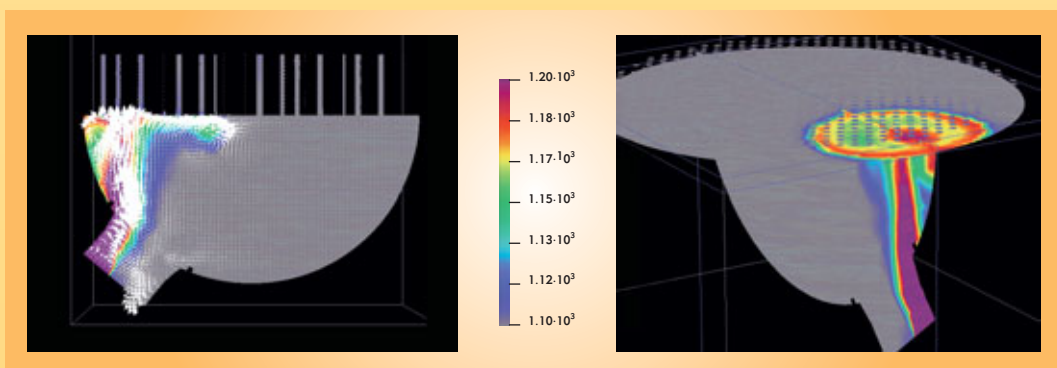


Figure E.

Computational resources for high-performance numerical simulation

B

Carrying out more accurate **numerical simulations** requires the use of more complex physical and numerical **models** applied to more detailed descriptions of the simulated objects (see Box A, **What is a numerical simulation?**). All this requires advances in the area of simulation software but also a considerable increase in the capacity of the computer systems on which the software runs.

Scalar and vector processors

The key element of the computer is the processor, which is the basic unit that executes a program to carry out a computation. There are two main types of processors, **scalar processors** and **vector processors**. The former type carries out operations on elementary (scalar) numbers, for instance the addition of two numbers. The second type carries out operations on arrays of numbers (vectors), for example adding elementwise the numbers belonging to two sets of 500 elements. For this reason, they are particularly well suited to numerical simulation: when executing an operation of this type, a vector processor can operate at a rate close to its maximum (peak) performance. The same operation with a scalar processor requires many independent operations (operating one vector element at a time) executed at a rate well below its peak rate. The main advantage of scalar processors is their price: these are general-purpose microprocessors whose design and production costs can be written-down across broad markets.

Strengths and constraints of parallelism

Recent computers allow high performances partly by using a higher operating frequency, partly by trying to carry out several operations simultaneously: this is a first level of **parallelism**. The speeding up in frequency is bounded by develop-

ments in microelectronics technology, whereas interdependency between the instructions to be carried out by the processor limits the amount of parallelism that is possible. Simultaneous use of several processors is a second level of parallelism allowing better performance, provided programs able to take advantage of this are available. Whereas parallelism at processor level is automatic, parallelism *between processors* in a parallel computer must be taken into account by the programmer, who has to split his program into independent parts and make provisions for the necessary communication between them. Often, this is done by partitioning the domain on which the computation is done. Each processor simulates the behavior of one domain and regular communications between processors ensure consistency for the overall computation. To achieve an efficient parallel program, a balanced share of the workload must be ensured among the individual processors and efforts must be made to limit communications costs.

The various architectures

A variety of equipment types are used for numerical simulation. From their desktop computer where they prepare computations and analyze the results, users access shared computation, storage and visualization resources far more powerful than their own. All of these machines are connected by networks, enabling information to circulate between them at rates compatible with the volume of data produced, which can be as much as 1 **terabyte** (1 TB = 10^{12} bytes) of data for one single simulation. The most powerful computers are generally referred to as **super-computers**. They currently attain capabilities counted in **tera-flops** (1 Tflops = 10^{12} floating-point operations per second).

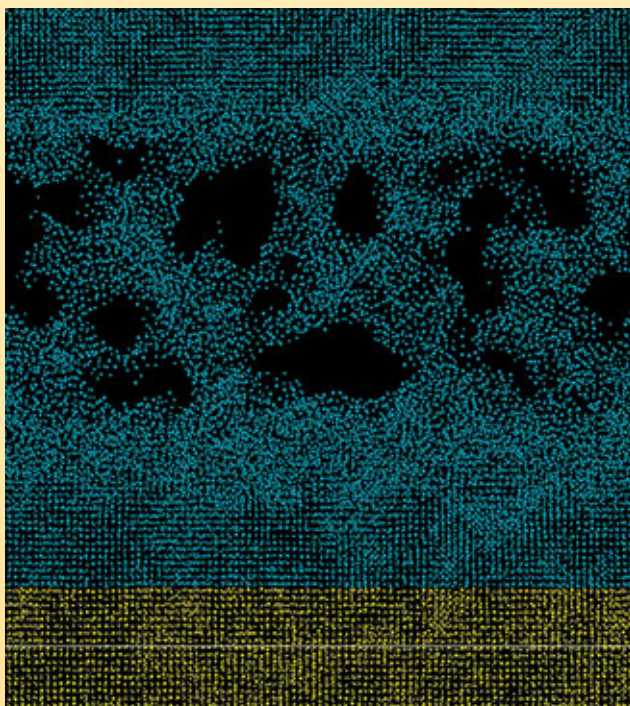
Currently, there are three main types of super-computers: vector supercomputers, clusters of mini-computers with shared memory, and clusters of PCs (standard home computers). The choice between these architectures largely depends on the intended applications and uses. Vector supercomputers have very-high-performance processors but it is difficult to increase their computing performance by adding processors. PC clusters are inexpensive but poorly suited to environments where many users perform numerous large-scale computations (in terms of memory and input/output).

It is mainly for these reasons that CEA's Military Applications Division (DAM) has chosen for its Simulation Program (see *The Simulation Program: weapons assurance without nuclear testing*) architectures of the shared-memory mini-computer cluster type, also known as **clusters of SMPs** (symmetric multiprocessing). Such a system uses as a basic building block a mini-computer featuring several microprocessors sharing a common memory (see Figure). As these mini-computers are in widespread use in a variety of fields, ranging from banks to web servers through design offices, they offer an excellent performance/price ratio. These basic "blocks" (also known as *nodes*) are connected by a high-per-



Installed at CEA (DAM-Ile de France Center) in December 2001, the TERA machine designed by Compaq (now HP) has for its basic element a mini-computer with 4 x 1-GHz processors sharing 4 GB of memory and giving a total performance of 8 Gflops. These basic elements are interconnected through a fast network designed by Quadrics Ltd. A synchronization operation across all 2,560 processors is completed in under 25 microseconds. The overall file system offers 50 terabytes of storage space for input/output with an aggregate bandwidth of 7.5 GB/s.

Computational resources for high-performance numerical simulation (cont'd)



CEA

Parallel computers are well suited to numerical methods based on meshing (see Box A, **What is a numerical simulation?**) but equally to processing *ab-initio* calculations such as this molecular-dynamics simulation of impact damage to two copper plates moving at 1 km/s (see Simulation of materials). The system under consideration includes 100,000 atoms of copper representing a square-section ($0.02 \mu\text{m}$ square) parallelogram of normal density. The atoms interact in accordance with an embedded atom potential over approximately 4–6 picoseconds. The calculation, performed on 18 processors of the Tera supercomputer at Bruyères-le-Châtel using the CEA-developed Stamp software, accounted for some ten minutes of “user” time (calculation carried out by B. Magne). Tests involving up to 64 million atoms have been carried out, requiring 256 processors over some one hundred hours.

formance network: the cumulated power of several hundreds of these “blocks” can reach several Tflops. One then speaks of a **massively parallel computer**.

Such power can be made available for one single parallel application using all the supercomputer’s resources, but also for many independent applications, whether parallel or not, each using part of the resources.

While the characteristic emphasized to describe a supercomputer is usually its computational power, the input/output aspect should not be ignored. These machines, capable of running large-scale simulations, must have storage systems with suitable capacities and performance. In clusters of SMPs, each mini-computer has a local disk space. However, it is not advisable to use this space for the user files because it would require the user to move explicitly his data between each distinct stage of his calculation. For this reason, it is important to have disk space accessible by all of the mini-computers making up the supercomputer. This space generally consists in sets of disk drives connected to nodes whose main function is to manage them. Just as for computation, parallelism of input/output allows high performance to be obtained. For such purposes, parallel overall file systems must be implemented, enabling rapid and unrestricted access to the shared disk space.

While they offer considerable computational power, clusters of SMPs nevertheless pose a number of challenges. Among the most important, in addition to programming simulation software capable of using efficiently a large number of processors, is the development of operating systems and associated software tools compatible with such configurations, and fault-tolerant.

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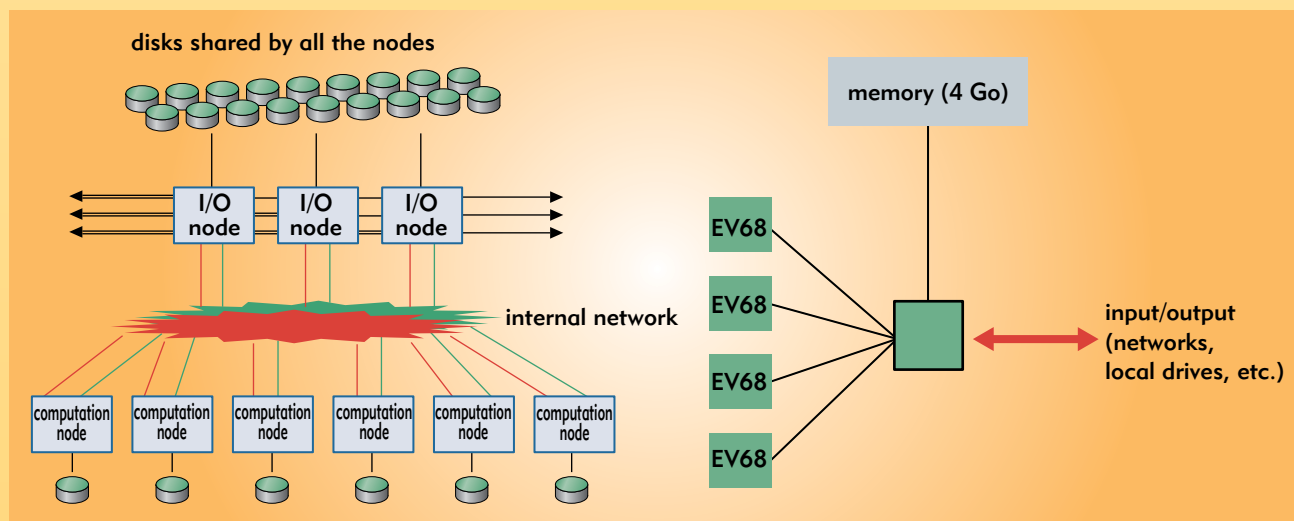


Figure. Architecture of an “SMP-cluster” type machine. At left, the general architecture (I/O = input/output), on the right, that of a node with four Alpha EV68 processors, clocked at 1 GHz.

Turbulence, or disturbance in so-called turbulent flow, develops in most of the flows that condition our immediate environment (rivers, ocean, atmosphere). It also turns out to be one, if not the, dimensioning parameter in a large number of industrial flows (related to energy generation or conversion, aerodynamics, etc.). Thus, it is not surprising that a drive is being launched to achieve prediction for the process – albeit in approximate fashion as yet – especially when it combines with complicating processes (stratification, combustion, presence of several phases, etc.). This is because, paradoxically, even though it is possible to predict the turbulent nature of a flow and even, from a theoretical standpoint, to highlight certain common – and apparently universal – characteristics of turbulent flows,⁽¹⁾ their prediction, in specific cases, remains tricky. Indeed, it must take into account the consi-

derable range of space and time scales⁽²⁾ involved in any flow of this type.

Researchers, however, are not without resources, nowadays, when approaching this problem. First, the equations governing the evolution of turbulent flows over space and time (Navier–Stokes equations⁽³⁾) are known. Their complete solution, in highly favorable cases, has led to predictive descriptions. However, systematic use of this method of resolution comes up against two major difficulties: on the one hand, it would require complete, simultaneous knowledge of all variables attached to the flow, and of the forced-flow conditions imposed on it,⁽⁴⁾ and, on the other hand, it would mobilize computational resources that will remain unrealistic for decades yet.

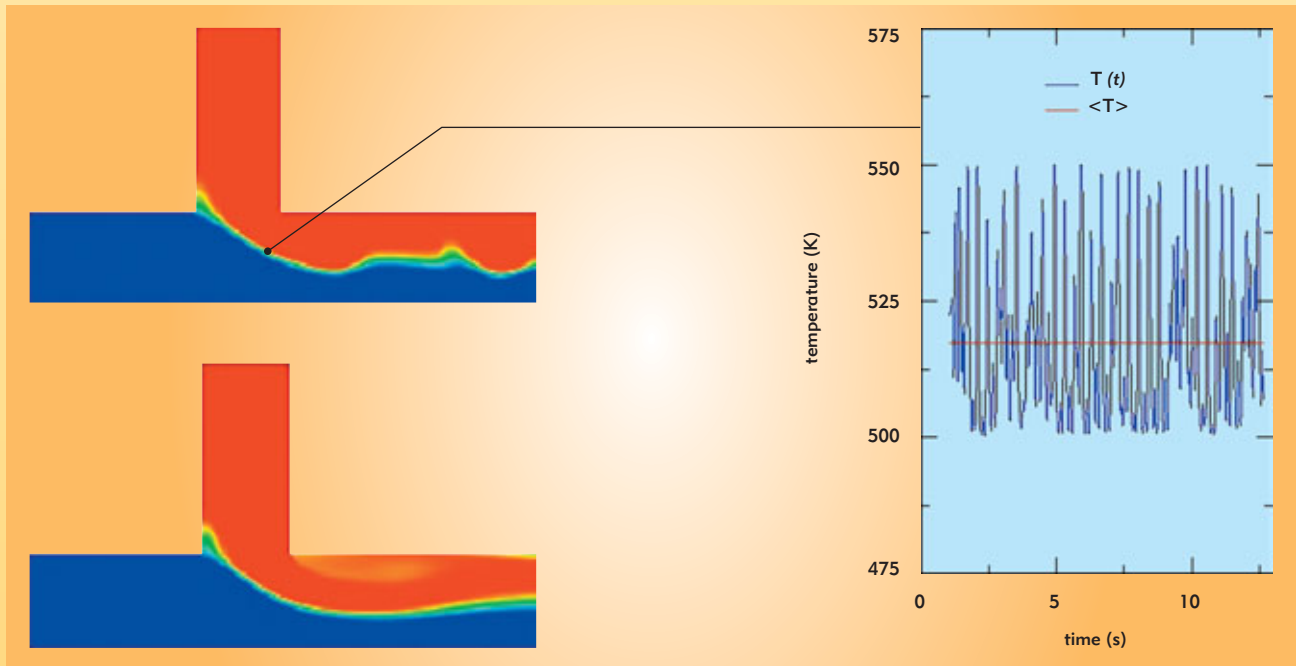


Figure. Instantaneous (top) and averaged (bottom) temperature field in a mixing situation. The curve shows the history of temperature at one point: fluctuating instantaneous value in blue and mean in red (according to Alexandre Chatelain, doctoral dissertation) (DEN/DTP/SMTH/LDTA).

The sole option, based on the fluctuating character of the flow due to turbulent agitation, must thus be to define and use average values. One of the most widely adopted approaches consists in looking at the problem from a statistical angle. The mean overall values for velocity, pressure, temperature... whose distribution characterizes the turbulent flow, are defined as the principal variables of the flow one then seeks to qualify relative to those mean values. This leads to a decomposition of the motion (the so-called Reynolds decomposition) into mean and fluctuating fields, the latter being the measure of the instantaneous local difference between each actual quantity and its mean (Figure). These fluctuations represent the turbulence and cover a major part of the Kolmogorov spectrum.⁽¹⁾

This operation considerably lowers the number of degrees of liberty of the problem, making it amenable to computational treatment. It does also involve many difficulties: first, it should be noted that, precisely due to the non-linearity of the equations of motion, any average process leads to new, unknown terms that must be estimated. By closing the door on complete, deterministic description of the phenomenon, we open one to modeling, i.e. to the representation of the effects of turbulence on mean variables.

Many advances have been made since the early models (Prandtl, 1925). Modeling schemas have moved unabated towards greater complexity, grounded on the generally verified fact that any new extension allows the previously gained properties to be preserved. It should also be noted that, even if many new developments are emphasizing anew the need to treat flows by respecting their

non-stationary character, the most popular modeling techniques were developed in the context of *stationary* flows, for which, consequently, only a representation of the flow's temporal mean can be achieved: in the final mathematical model, the effects of turbulence thus stem wholly from the modeling process.

It is equally remarkable that, despite extensive work, no modeling has yet been capable of accounting for all of the processes influencing turbulence or influenced by it (transition, non-stationarity, stratification, compression, etc.). Which, for the time being, would seem to preclude statistical modeling from entertaining any ambitions of universality.

Despite these limitations, most of the common statistical modeling techniques are now available in commercial codes and industrial tools. One cannot claim that they enable predictive computations in every situation. They are of varying accuracy, yielding useful results for the engineer in controlled, favorable situations (prediction of drag to an accuracy of 5–10%, sometimes better, for some profiles), but sometimes inaccurate in situations that subsequently turn out to lie outside the model's domain of validity. Any controlled use of modeling is based, therefore, on a qualification specific to the type of flow to be processed. Alternative modeling techniques, meeting the requirement for greater accuracy across broader ranges of space and time scales, and therefore based on a "mean" operator of a different nature, are currently being developed and represent new ways forward.

The landscape of turbulence modeling today is highly complex, and the unification of viewpoints and of the various modeling concepts remains a challenge. The tempting goal of modeling with universal validity thus remains out of order. Actual implementation proceeds, in most cases, from compromises, guided as a rule by the engineer's know-how.

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(1) One may mention the spectral distribution of turbulent kinetic energy known as the "Kolmogorov spectrum," which illustrates very simply the hierarchy of scales, from large, energy-carrying scales to ever smaller, less energetic scales.

(2) This range results from the non-linearities of the equations of motion, giving rise to a broad range of spatial and temporal scales. This range is an increasing function of the Reynolds number, Re , which is a measure of the inertial force to viscous force ratio.

(3) The hypothesis that complete resolution of the Navier–Stokes equations allows simulation of turbulence is generally accepted to be true, at any rate for the range of shock-free flows.

(4) This is a problem governed by initial and boundary conditions.

Advances in software engineering

In the early days of scientific computation (in the period 1950–70), the physicist would be a “jack of all trades”: physical and mathematical **modeling, numerical analysis**, programming, use of the tool once developed, analysis of the results (see Box A, **What is a numerical simulation?**).

Then, the complexity of the problems addressed, the need to control result accuracy and the stability of **numerical methods**, the quest for minimizing computation times (up to *real time* nowadays) led to “numericists” providing support to physicists for the design of **computation codes**. This evolution naturally raised a few temporary difficulties: the activity became a cross-disciplinary effort, and physicists lost some of their autonomy, giving place to synergy between two cutting-edge areas of expertise.

Then, the problems grew even more in scope and complexity: nowadays, nuclear reactor cores are calculated with the description of every one of the 40,000 **fuel** rods of varying composition and, simultaneously, of the **turbulent** water–steam flow surrounding them! (Box F, **Modeling and simulation of turbulent flows**.) Issues of ergonomics, flexibility of use, sequencing, coupling and adaptation to computers with rapidly changing architectures also had to be addressed (see Box B, **Computational resources for high-performance numerical simulation**). In turn, the integration of this third domain of expertise, software engineering, enabling more accurate or more relevant calculations, brought some organizational difficulties of its own.

The three areas of expertise (physics, numerical analysis and software engineering) are of course closely interwoven, and the know-how of each one directly impacts the others. It has become crucial to train engineers and researchers to master

at least two of these domains, while having better than rudimentary knowledge of the third.

Within the framework of joint development by CEA and EdF of new computation and modeling platforms for nuclear power generation (**neutronics, thermalhydraulics**, fuel), the software architecture is just as important as physical models, numerical methods, or qualification. The issue has been examined for each individual project and globally between projects over a two-year period, ultimately leading to a five-level common architecture that will take on board user requirements for ergonomics, while enabling the physicists and numericists to express their know-how in optimum fashion.

These five software layers govern transitions between “real-world objects” (a fuel assembly, a steam pipe, etc.) and computational objects (**meshes**, arrays, solvers, fields, etc.).

The distance covered is vast, since the initial calculations performed in the 1950s on a slide rule and mainly based on rules of three, and today’s calculation codes that can solve non-linear systems of **partial differential equations** on **supercomputers**. The physicist’s and the engineer’s know-how nevertheless remains intact: such is the experimental validation, whether intuitive or deductive, of the mathematical and physical modeling devised and integrated into the calculation codes. The true physicist retains the ability to predict and verify the orders of magnitude of the results yielded by these codes... using rules of three!

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Doses and dose rates

In a hostile environment, sources of **radioactivity** emit radiation (X, γ radiation) and/or particles (α , β particles, neutrons), which propagate and interact with the elements they encounter. These interactions respect probabilistic laws depending on the nature of the target material (atomic makeup) and particle or radiation properties (direction of propagation and energy level).

Interactions with equipment or an operator yield energy, part of which is shed *in situ*. This part is expressed as a **dose**, and corresponds to the quantity of energy imparted to the material per unit mass. Units are the **gray** (legal unit) and rad (old unit): $1 \text{ Gy} = 100 \text{ rad} = 1 \text{ J/kg}$. For a human operator, the biological effect varies according to the radiation and nature of the tissue. Use is then made of the **dose equivalent** concept, this being expressed in **sieverts** (legal unit) or rems (old unit): $1 \text{ Sv} = 100 \text{ rem}$. The **dose rate** (legally expressed in Gy/s, and frequently in Gy/h or rad/h) for the effect on equipment, or the **dose equivalent rate** (in Sv/h or rem/h) for the effect on a person represent respectively the absorbed dose and absorbed dose equivalent per unit time.