

LETTERS

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Underground Nuclear Testing, Continued?

Your Washington Reports story on the Strategic Arms Reduction Treaty (August 1991, page 49) reported briefly on an exchange between Sidney Drell and myself on whether the safety problems of the nuclear warheads in the US nuclear stockpile require continued underground nuclear testing. Unfortunately, the description of this exchange was too brief to characterize adequately either Drell's position or my own. Drell has written to clarify his position (November, page 9), and I would like to take this opportunity to do the same.

My position is that the US should stop testing by 1995 unless there are very strong reasons not to do so. The Nonproliferation Treaty must be renewed in that year, and a significant fraction of the non-nuclear-weapon signatory states made it clear at the 1990 NPT review conference that they would support the strengthening of the nonproliferation regime only if the nuclear-weapon states commit themselves to a comprehensive test ban treaty. The Bush Administration has refused to make this commitment and has put special emphasis on the need to test in order to increase the safety of US nuclear warheads.

There have been two independent reviews of the safety issue—both commissioned by Congressional groups. The first was carried out by a committee headed by Drell.¹ The second was carried out by a retired Livermore physicist, Ray Kidder.²

Kidder noted that with the scheduled retirement of older US nuclear warheads, only three warheads in the US nuclear arsenal will not be equipped with the principal safety design features in modern US nuclear

warheads: enhanced electrical isolation and insensitive high explosives. He also concluded that the three warheads could be replaced or rebuilt to modern safety standards and tested well before 1995 and that this would require less than 20 tests. He believes that the stockpile would then be adequately safe.

The Drell panel was not sure whether this measure would provide enough safety and urged that the weapons labs be encouraged to explore "inherently safe" designs—a program that would prolong testing well beyond 1995. The example of an inherently safe design the panel gave was one in which the plutonium core of the fission trigger would only be emplaced inside the chemical implosion system when the warhead was armed. If the plutonium were well shielded before this, an accidental explosion of the chemical implosion system could neither cause a nuclear explosion nor disperse a dangerous aerosol of plutonium oxide.

However, there are much simpler ways to "mechanically safe" a nuclear warhead, that is, to assure that there won't be a nuclear explosion even if the implosion system is detonated. For example, a neutron-absorbing material could be introduced into the center of the hollow plutonium sphere and only be withdrawn when the warhead was armed. This type of mechanical safing is well understood and requires no nuclear testing at all.

The remaining risk is the possibility that a chemical explosion or fire might result in the release of a plutonium oxide aerosol. The former case would be much more serious, since an explosion could create a more widely dispersed aerosol with smaller, more inhalable particles.

Steve Fetter and I therefore estimated the consequences of a worst-case accident of this type in which 10 kilograms of plutonium was converted into an inhalable plutonium oxide aerosol by the detonation of the chemical explosives in several nuclear warheads.³ We assumed that this happened at the Bangor Trident submarine base, just 30 kilometers from downtown Seattle. Depending upon atmospheric conditions and the value of the cancer exposure risk coefficient used, we found that from 1 to 1200 extra cancer deaths could result over the remaining lifetime of the exposed population. Individual risks of cancer death in this exposed population would typically be increased by a few tenths of a percent or less.

Historically there have been only two such accidents, and they took

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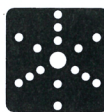
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place in much less densely populated areas. These resulted from the crashes in Spain in 1966 and on the ice off Thule, Greenland, in 1968 of two B-52s on airborne alert carrying bombs containing sensitive high explosives. In the absence of such dangerous practices and with an arsenal containing only insensitive high explosives, the risk of such an accident is would be exceedingly low.

The question therefore is whether this residual risk is worth continuing a billion-dollar-a-year nuclear war-head design and testing program and seriously undermining the nonproliferation regime. In my view it is not. We can save a lot more lives investing the money elsewhere.

References

1. S. D. Drell, J. S. Foster Jr, C. H. Townes, report of the Panel on Nuclear Weapons Safety to the House Armed Services Committee (December 1990).
2. R. E. Kidder, "Report to Congress: Assessment of the Safety of US Nuclear Weapons and Related Nuclear Test Requirements," UCRL-LR-107454, Lawrence Livermore Natl. Lab., Livermore, Calif. (July 1991).
3. S. Fetter, F. von Hippel, *Science and Global Security* 2, 21 (1990).

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DRELL REPLIES: Frank von Hippel and I differ only in his certainty that it will be possible to meet and subsequently maintain appropriately conservative safety criteria for our nuclear weapons in time for a comprehensive test ban treaty in 1995. I do not believe that we can say that *now*.

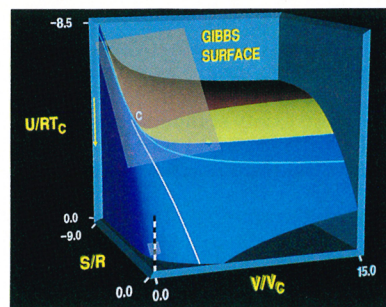
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Gibbs's Models Visualized

Martin Klein's lucid account of J. Willard Gibbs's contributions to classical thermodynamics (September 1990, page 40) suggests a question that has only recently become resolvable: Why not make use of the Gibbsian models to explain how thermodynamic functions are related and thus remove some of the abstraction that students perceive without these visual aids?

In the past, thermodynamic models have been too difficult to construct, particularly in pedagogically meaningful groupings. While the one-of-a-kind models that we have had are useful (Maxwell's famous energy-en-



tropy-volume surface,¹ later examples by Heike Kamerlingh Onnes and Wilhelmus H. Keesom² and by Arthur L. Clark and Leon Katz,³ and the molded pressure-volume-temperature surfaces available today, they stand alone and give no hint of interconnectedness. Because the transformations coupling them imply conformity to second and higher derivatives, hand modeling is too imprecise to yield geometrically coherent structures. Yet it is just this coherence (naively perceived as a kind of circularity) that enables thermodynamic data to pass through these geometries unaltered.

Using computer graphics, we are re-creating Gibbs's models, not only to develop a much needed teaching resource but also to preserve a crucial, unique component of the Gibbsian approach. While machine-based visualization is becoming a standard tool in research, it was unheard of in the 1870s. Indeed Gibbs, with his keen ability to couple physical and mathematical ideas to graphic images, may have been among the earliest scientific visualizers.

Combining computational thermodynamics with high-performance graphics, we have focused on Gibbs's original models and produced three-dimensional drawings of pure-fluid structures in the fundamental coordinate systems *USV*, *ATV*, *HSP* and *GTP*. (We follow conventional symbolism: *U* for energy; *S*, entropy; *V*, volume; *A*, Helmholtz energy; *T*, temperature; *H*, enthalpy; *P*, pressure; and *G*, Gibbs energy.) We use color to partition the surfaces according to stability levels and transparency to illustrate the tangencies with which Gibbs characterized the phase-splitting process.⁴

The figure above shows the energy-entropy-volume surface for the fluid phases of ethylene as generated from a cubic *PVT* equation (the Peng-Robinson⁵) and a temperature-dependent heat-capacity expression. Stable, metastable and unstable states, colored blue, yellow and red, respec-

tively, join at the fluid-phase critical point (marked "C" in the drawing). A light-blue curve traces the critical isotherm, and a white constant-pressure line runs from the critical region to the high temperatures in the foreground. Data are nondimensionalized using critical-point values.

Gibbs's geometrical method for coexisting phases is illustrated with a transparent tangent plane that straddles the depression resulting from the changed convexity in the unstable region. The plane's two points of tangency (marked with diamond cut-outs) share the same principal slopes $[(\partial U/\partial S)_V = T, (\partial U/\partial V)_S = -P]$ and project to the same intercept on the *U* axis (where the like-colored chip cuts the checkered pole). In these scaled coordinates this last quantity represents the chemical potential μ (which equals $G = U - TS + PV$ for a pure fluid). The respective equalities of *T*, *P* and μ guarantee equilibrium between the states represented by the tangent points, and Gibbs showed how such splitting is consistent with entropy maximization in isolated systems.

As the tangent plane rolls to the left or right of the position shown, this geometrical situation persists, and the moving tangencies describe the two branches of the vapor-liquid coexistence curve (the blue-yellow boundary). The models described in references 1 and 3 show the more complete *USV* geometry that gives rise to vapor-solid and solid-liquid equilibria and that demonstrates the confluence of the two-phase regions to form a triple point (shown schematically in Klein's article in a two-dimensional entropy-volume projection).

Moving this scenario into coordinate systems where temperature or pressure become independent variables is the function of the Legendre transform. We have used our computer graphics technique also to recast the *USV* information into Helmholtz energy, enthalpy and Gibbs energy models, forms that not only preserve the information but also relate it more obviously to the controls imposed in practical processes.⁶

We are now extending the work to fundamental functions for mixtures and coping with the hyperdimensionality by constructing families of three-dimensional parametric sections. The extra effort associated with visualizing thermodynamic ideas in these more complex coordinate systems is rewarded by the satisfaction of seeing, once and for all, how such elusive concepts as chemical potential equality and the hierarchi-