Hurricane Seeding

The article "The decision to seed hurricanes" by Howard *et al.* (*1*) reveals a significant dilemma at the interface between technology and society. The costs associated with hurricanes that strike our shores and the potential benefits to society if these hurricanes can be diminished in force are great. But under present law those who might be empowered to seed hurricanes are forbidden to do so.

In the article only property loss is considered, and it is assumed that the warning systems available in the United States are adequate to save lives. It is true that hurricanes have generally caused fewer losses of life as warning systems have improved. In Hurricane Camille (1969), the largest of the recent hurricanes, those who lost their lives near the coast had chosen to ignore the available warnings. In Virginia, loss of lives in flash floods induced by Camille occurred where the data gathering facilities (and population) were sparse, and there was no warning or only a few minutes warning. (Seeding Camille would not have made a difference to Virginia, but it is not clear that Virginians would have accepted this judgment.) We have not yet had the experience of a hurricane the size of Camille bearing down on an area of congested population. If Camille had swerved westward and passed over New Orleans, the story might have been much different. There is a serious question as to whether, even with a 15-hour notice, the city of New Orleans could be entirely evacuated and the population properly protected from a hurricane of this size. If we considered the loss of life in recent typhoons (hurricanes) in India and Pakistan, a higher set of costs would be associated with the not-seeding alternative in a hurricane seeding decision analysis.

The U.S. government has a grave responsibility to move forward the work on hurricane seeding. We are the major world power most actively engaged in this kind of research. Progress in taming hurricanes is likely to be viewed around the globe as a positive contribution and, in view of the diminished role of the United States in world affairs, such contributions are timely. In addition, the hurricane modification issue is not contaminated by a number of political features: (i) It has nothing to do with the war in Vietnam. (ii) It is not being aggressively proposed by anyone who stands to profit from a change in government policy. (iii) There is no strongly organized crusade on either side of the issue. (iv) All but a minuscule proportion of our population would subscribe to the proposition that, if we can reduce the force of a hurricane, we should do so.

But beyond the question of whether or not the government should interfere with a hurricane, there is another issue, that of the use of decision analysis itself. By providing a unique structure for technical discussion, the article by Howard *et al.* sets a precedent for the resolution of social questions involving technical risk on a large scale. Because the decision analysis format has not heretofore been used in open public debate, there may be some who object to having the conversation thus structured. These objectors should be made aware that there has been considerable research on this question. It has been shown that if there is to be a group decision on a subject, and if it is desired to avoid ambiguity, inconsistency, ad hoc procedures, and dishonesty, then decision analysis techniques provide a unique method for doing so (*2*). Decision analysis separates questions of value from questions of fact and makes the structure of decision-making and its consequences transparent. It forces judgment to be made in the open and does not permit the hidden mixing of value judgments with professional expertise. The Operations Research Society of America has turned its attention to the whole question of the role of the "expert witness" before Congress and has stressed the importance of separating fact from opinion, of revealing bias, and of coping with the adversary proceedings so favored by Congress (*3*). I hope that after the scientific discussions of this subject (which I trust will be sparked by the publication of the decision analysis) there will be congressional investigations into the issue of hurricane modification. Congress has not yet addressed the broad issues raised in the report, especially those which deal with the legal rights of the government and its citizens. Until Congress acts, the position of the decision-makers, that is, officials of the National Oceanic and Atmospheric Administration and the Navy, remains ambiguous. They are now forbidden to seed hurricanes that endanger our shores.

Those who will be called on to testify before Congress can benefit from the opinion of the scientific community in regard to the issues raised in the article. But such opinions will be of little value if they are broad endorsements or blanket condemnations. What is needed is additional information structured in the form of the decision analysis. There may be those who would propose different probability distributions, different prior probability assignments, or different values for the outcomes. Perhaps a larger variety of outcomes needs to be considered. These are areas in which men can usefully disagree. Through the decision analysis, it is possible to see whether such disagreements lead to different decisions.

With a complex phenomenon, such as a hurricane, with the attendant problems of observation and calculation, there is ample room for different interpretations. Recall that a typical hurricane is 30 km in diameter across the eyewall, reaches from near sea level to the stratosphere, has "arms" that often stretch almost from Africa to North America, and transforms more energy than several atom bombs. Satellite photographs show gross details on a scale of hundreds of kilometers. Aircraft radar probes give localized data, from which many features of the storm may be inferred, but the largest jet airplane is a tiny probe and it can give only a "sliced-time-snapshot" of the hurricane.

The analytical side is beset with difficulties, too. The available computers are not big enough or fast enough to include all we really know about fluid mechanics and cloud physics. The fluid mechanical phenomena are on such a fine scale that there are inherent barriers to the development of mathematical models that truly represent all we know.

There is a simple qualitative explanation of why seeding should offset a hurricane (*4*). The addition of silver iodide crystals is expected to nucleate supercooled water, release heat of fusion, and create buoyancy forces which then distort the centrifugal field. The net result is that the eyewall becomes somewhat larger because of moment of momentum considerations (or because of changes in the pressure gradient) and the velocity of the peak wind decreases. Rosenthal (*5*) and his colleagues have made numerical computations on the behavior of a hurricane with seeding. Despite the approximations involved, the development of the velocity distribution in the storm as observed by aircraft traversing the hurricane and as predicted by the computer was remarkably similar, not only in shape but also in magnitude (6). The impact of such information is discussed in (7).

But even if the facts are better known they do not define the responsibilities of the decision-maker and his liability to those who think that his actions have increased their exposure to danger. The problem of dealing with claimants is compounded by the forecaster's limited ability to predict the track and intensity of a hurricane 12 to 15 hours in advance. When a hurricane comes ashore, it may spawn a few small tornadoes with localized winds much higher than those predicted by the forecaster. With the limitations on achievable instrumentation and the necessity to warn the public in simple terms, the forecast must appear incorrect (one way or another) to many observers. No forecaster can appear to be infallible to a majority of those affected, even if he has skills no forecaster now possesses.

Clearly, legislation should be drawn up to clarify the responsibilities of the decision-makers. One proposal is that legislation establish a decision board empowered to decide on each hurricane threat. This decision board could be legally freed of liability from public suits by congressional enactment, provided the board acted in accordance with provisions established in conjunction with the elected representatives of the regions likely to be affected by the hurricane. For example, the legislature or the governor of the State of Florida could appoint a committee which would meet with the hurricane decision board and agree to the rules that would be used in deciding whether a hurricane should be seeded when it threatened that state. When a hurricane approached the Florida coastline, the decision board could then be summoned to give an on-the-spot decision. There would also have to be compacts between neighboring states to take into account hurricanes that approach or cross state borders. The entire process would have to be supervised by the federal government since it would involve compacts among the states and would involve the use of federal facilities.

Whatever the final form of appropriate legislation, its development will require the participation of representatives of many disciplines and many interests. It is hoped that through the decision analysis format the discussions can be carried forward in a rational manner. If this should prove to be the case, we will have witnessed the beginning of a new approach to the treatment of problems involving technology and society.

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The Thermodynamics of Gases Dissolved at Great Depths

In a recent report (*1*) Fenn calculated the equilibrium partial pressure of dissolved gases in water at great depths, and he requested a thermodynamic derivation and a physical explanation of the exponential equation he employed. It is my purpose in this technical comment to demonstrate the derivation of a rigorous expression for gas solubility at high hydrostatic pressures, and to give a physical interpretation of its form in terms of molecular thermodynamics.

The basis for such a derivation is the proper definition of the reference state in Henry's law, leading to the derivation of the classical Krichevsky-Kasarnovsky equation (*2*). Instead of partial pressure, it is more general to work in terms of the fugacity f (*3*), stating Henry's law as (*4*)

$$\ln \frac{f_2}{x_2} = \ln H_{2,1} + \frac{\bar{v}_2^{\,\infty} (P - P^0)}{RT} \quad (1)$$

where the subscript 2 refers to the solute and the subscript 1 refers to the solvent, x is the mole fraction, $H_{2,1}$ is the constant of Henry's law, and R is the gas constant. The reference state conditions for $H_{2,1}$ must be defined exactly, and these are taken to be infinite dilution of solute in solvent at the temperature T and at some reference pressure P^0. Normally P^0 is chosen (for convenience) as a pressure of either 1 atm or zero, or as the solvent vapor pressure.

The final term in Eq. 1 is the Poynting correction, which takes into account the fact that even isothermal pressure changes alter the reference condition, and a correction term must be added. The change in fugacity due to an isothermal variation in pressure is given in terms of the change of Gibbs energy Δg as

$$RT \ln \frac{f_2}{f_2^0} = \Delta g = \int_{P^0}^{P} \bar{v}_2 dP \quad (2)$$

where f_2 is the fugacity of the solute at pressure P and f_2^0 is the fugacity at the reference pressure P^0. Also $\bar{v}_2$ is the partial molal volume of the solute in solvent, and at the reference composition this is taken as the infinite dilution value, $\bar{v}_2^{\,\infty}$. Normally, this quantity $\bar{v}_2^{\,\infty}$ is assumed to be independent of pressure; this assumption is quite justifiable for solutions in the relatively incompressible solvent water, up to pressures of the order of about 1 kb, the maximum ocean pressure encountered.

The isothermal variation of fugacity in a potential field can be shown to be (*5*)

$$f_2 = f_2^0 \exp\left(\frac{Mgd}{RT}\right) \quad (3)$$

where M is the molecular weight of the solute, and the pressure varies with depth d in terms of the density ρ of seawater

$$P = P^0 + \rho g d \quad (4)$$

where we assume for convenience that the surface pressure P^0 is taken as the reference pressure. If we further assume that the ideal gas law is a good approximation for the fugacity of the solute gas at the low surface pressure P^0, then combination of Eqs. 1 to 4 results in the expression

$$x_2 = \frac{P^0}{H_{2,1}} \exp\left[\frac{(M - \rho\bar{v}_2^{\,\infty})gd}{RT}\right] \quad (5)$$

This exponential result is equivalent to Fenn's equation 1, and, as he showed, since M (32 for O_2) is very close to the product of the seawater density ($\rho = 1.023$ g/cm^3) and the partial molal volume of O_2 ($\bar{v}_2^{\,\infty} = 32$ cm^3/mole), the variation of O_2 concentration with depth is slight, although