The Impact of Nuclear Power on Air and Water Resources

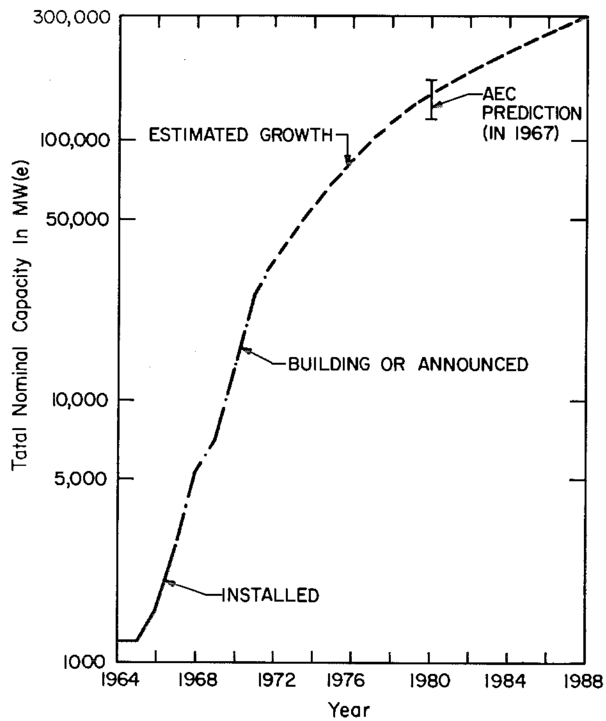
by Jack E. McKee

The rapid growth of nuclear power plants in the United States raises serious questions about the environmental factors involved in their operation.

The sudden surge toward nuclear power throughout the world has given rise to some serious questions about its potential effect on many facets of our complex civilization. The social, economic, military, and geopolitical implications are staggering and far beyond the comprehension of most of us. Of immediate and practical concern to all, however, is the impact of nuclear power on our local environment, and specifically on the quality of air and water resources. It is prudent, therefore, to evaluate the probable effects of routine discharges from nuclear power plants on the atmosphere and on natural waters and to assess the possible consequences of a serious accidental discharge of radioactivity.

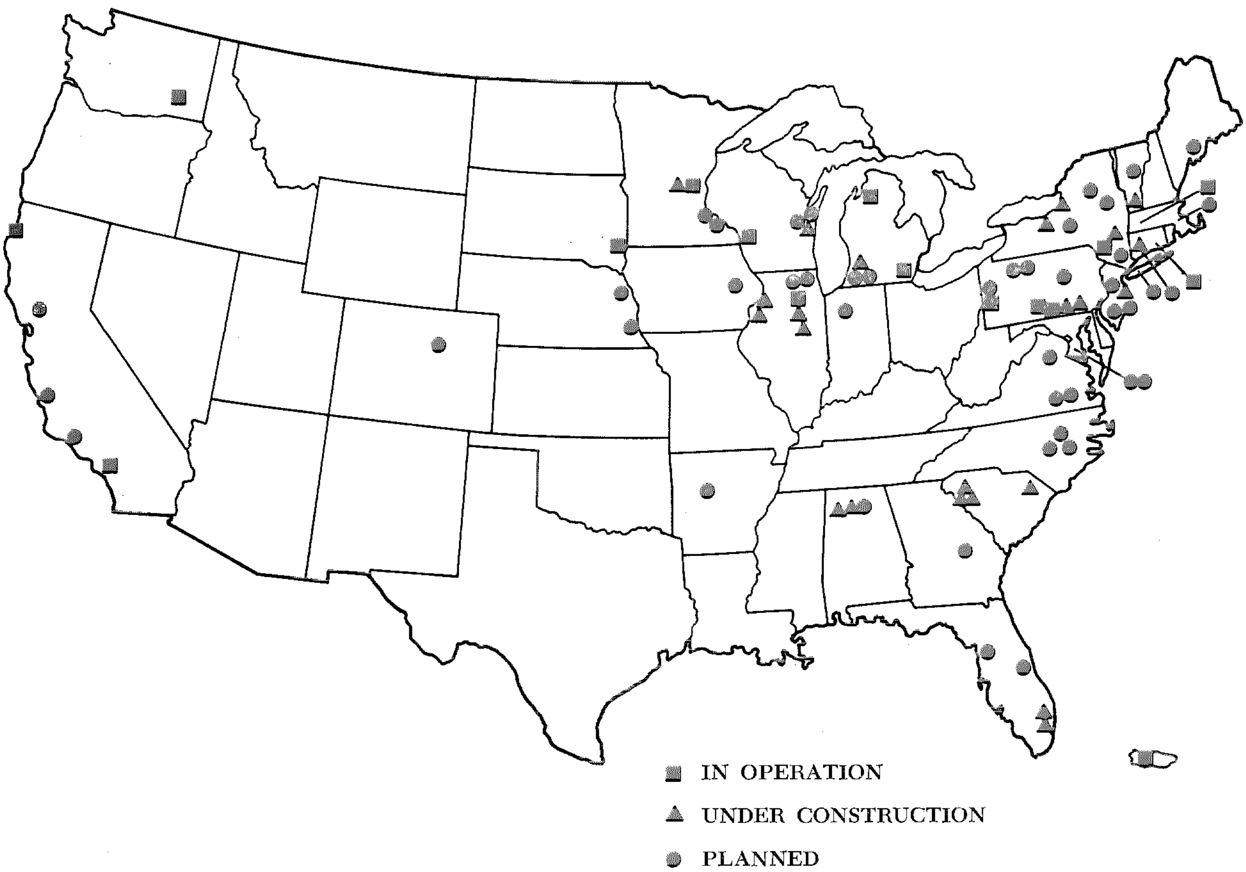
The past, present, and probable future growth of commercial nuclear power in the U.S. is shown at the right. It is estimated that by 1980 the installed nuclear capacity will be about 100,000 electric megawatts [MW(e)] or about 37 percent of the then total electric capacity. By the turn of the century, more than half of the capacity will probably be nuclear.

Estimated Future Growth of Commercial Nuclear Power



In order to weigh the probable and potential impact of commercial nuclear power on the environment, let us consider the major types of nuclear reactors and the nature of their waste products. Almost all large commercial nuclear power reactors in the United States utilize enriched uranium for fuel and ordinary light water for primary cooling and heat transfer. These reactors are categorized into two types, *viz.* pressurized-water reactors (PWR), which account for about 60 percent of the total, and boiling-water reactors (BWR).

NUCLEAR POWER REACTORS IN THE UNITED STATES

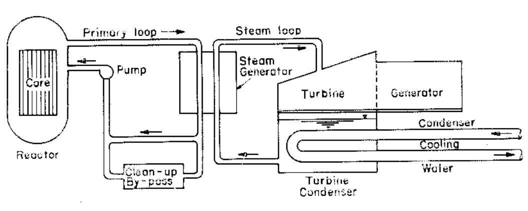


In a PWR (below) the circulating primary coolant water reaches a temperature of about 600°F, but it does not boil because the pressure is held at about 2,000 pounds per square inch (psi). Steam is generated in the secondary loop by means of a heat exchanger or steam generator. The condenser cooling water system is of special note, for this is where one of the major impacts on the environment occurs.

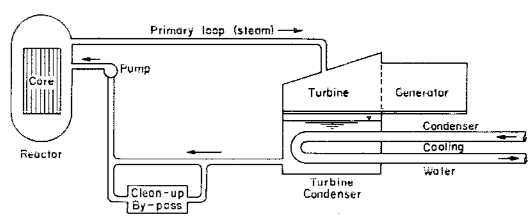
A boiling-water reactor (right) operates at a lower pressure (about 1,000 psi) which allows the water to boil at temperatures of about 500°F. Thus, a secondary loop is not necessary, but there must still be a condenser cooling system. It might appear that boiling-water reactors are much simpler than pressurized-water reactors, but there are many complicating and compensating factors related to safety and waste discharge.

The primary coolant in both PWR and BWR

PRESSURIZED-WATER REACTOR



BOILING-WATER REACTOR



plants is ordinary demineralized water to which may be added small concentrations of boric acid for neutron absorption and phosphates for pH control. The enriched uranium-oxide pellets and their fission products are normally confined in fabricated fuel elements by cladding or coating of stainless steel or Zircaloy. Because of the high temperature and the low mineral content of the primary coolant water, however, corrosion and leakage of the cladding or piping may occur. As a result the primary coolant eventually acquires fission products that leak from the fuel elements and corrosion products (crud) that come from the metal system.

To remove these fission products and circulating crud, part of the primary coolant is diverted through a treatment system utilizing diatomite filters and ion-exchange resins. The used diatomite and spent resins are generally not recovered or regenerated, but are hauled offsite for regulated land disposal.

Liquid wastes. Although the primary loop of a PWR or BWR is normally a "bottled-up" system, overflow of water occurs when the boron concentration must be lowered by dilution. Moreover, small leaks may occur at valves or other fittings, or around pump seals. Radioactive liquids may also originate in the laboratory or washrooms. All such spillage, leakage, and drainage is collected and subjected to treatment before discharge to the environment or prior to controlled offsite disposal. The total volume of such liquid wastes is relatively small, but highly variable. It should seldom exceed 100,000 gallons per day (gpd) for a 500 MW(e) reactor and can be expected to average less than 50,000 gpd. The total radioactivity in the untreated liquid wastes may also be expected to be low, probably not in excess of 10 to 20 curies per year, mostly in the form of activated corrosion products (e.g. Fe-59, Mn-54, Co-58, Cr-51, Mo-99).

Treatment generally comprises detention for the stabilization of isotopes of short half-life, steam stripping of dissolved gases, diatomite filtration, contact with ion-exchange resins, and/or evaporation. The treated liquid is then monitored for radioactivity and, if acceptable, diluted in the condenser cooling water system for discharge to a river, lake, or ocean. Spent resins, contaminated diatomite, and evaporator residues are hauled offsite to regulated land-disposal areas.

Gaseous wastes. Neutron activation of the primary coolant water in PWR's and BWR's will cause a radiolytic production of gaseous radioisotopes of nitrogen, oxygen, fluorine, and hydrogen (tritium). If the water coolant is not well-deaerated, radioisotopes of the rare gases (argon, krypton, xenon) and possibly carbon oxides will be produced in small amounts. Moreover, defects in the fuel-element cladding may cause leakage of gaseous fission products (bromine, iodine, krypton, xenon) to the primary coolant.

The primary coolant water in a PWR is generally supersaturated with hydrogen gas to minimize radiolysis. The short-lived radioisotopes of nitrogen, oxygen, and fluorine that are still produced are kept in solution and recycled sufficiently to cause almost complete decay. Some waste gases are released, however, in the by-pass cleanup circuit and in the overflow resulting from boron dilution. Since such waste gases are mostly hydrogen, catalytic burners are used to convert the hydrogen to water for subsequent decay in hold-up tanks or for disposal as a liquid waste. The remaining gases are generally filtered to remove solid particulate daughter products and discharged through short stacks to take advantage of atmospheric dilution. In general, gaseous wastes are an almost insignificant problem at a PWR, unless and until there is considerable leakage of noble gases through perforated cladding of fuel elements.

For boiling-water reactors, however, the gaseous wastes constitute the major routine impact on the environment. Hydrogen cannot be kept in the primary coolant of a BWR, and therefore the production of radiolytic gases is enhanced. The short-lived isotopes of oxygen, nitrogen, and fluorine, along with noble gases from perforations in fuel elements, transfer as non-condensible gases with the steam and are removed from the primary circuit through the turbine-condenser air vents. The higher halogens and the particulate solid daughters from decay of krypton and xenon generally remain in the primary coolant and are removed eventually in the by-pass cleanup circuit.

The so-called off gas from the turbine condenser is generally stored in holdup tanks for about 30 minutes to permit decay of the short-half-lived isotopes of nitrogen, oxygen, fluorine, xenon, and most krypton radioisotopes. The solid daughters formed in the off-gas lines and holdup tanks are removed by filtration, and the residual gas is then monitored and discharged to the atmosphere through tall stacks to achieve maximum atmospheric dilution. The filters are replaced frequently and hauled offsite as a solid radioactive waste.

The major radioisotope remaining in the stack discharge from a BWR is Kr-88, which has a half-life of 2.8 hours. Fortunately, a longer, half-lived isotope, Kr-85, is present only in minute traces. Owing to the high rate of off-gas production, however, it is possible for the radioactivity of the stack gases of a large BWR to reach 1.0 curie per second (86,400 curies per day) if one percent of the fuel elements develop perforations. Such releases would call for shutdown of the reactor and replacement of the perforated fuel elements.

Solid wastes. Spent diatomite, ion-exchange resins, evaporator concentrates, and other noncombustible high-activity wastes are generally fixed in concrete in 55-gallon drums and turned over to commercial firms for offsite land disposal at regulated locations in Kentucky, Nevada, New York, and Washington. Light combustible wastes such as fiber filters are generally baled, sealed in drums or boxes, and shipped offsite for land disposal. The present regulated locations for land disposal of such solid wastes appear to be ample for all conceivable future nuclear power plants.

All releases of radioactivity into the environment are controlled by the Atomic Energy Commission in compliance with the guides or standards of the Federal Radiation Council, the National Council on Radiation Protection and Measurement, and the International Commission on Radiological Protection. The specific AEC rules are set forth in the Code of Federal Regulations, Title 10, Part 20.

The meat of the rules is in a table which delineates the allowable radioactive concentration of each isotope discharged through a stack, pipe, or similar conduit at the point where the material leaves the conduit. If the conduit discharges within a restricted area, the concentration at the boundary may be determined by applying appropriate factors for dilution, dispersion, and/or decay between the point of discharge and the boundary.

For water, the regulations generally apply in the condenser cooling water into which liquid wastes have been diluted. Since no attempt is made to measure all radionuclides in the effluent, the gross limit in the condensing water effluent, for all practical purposes, is 100 picocuries per liter (pc/1). Concentrations, however, may be averaged over a period of one year. Experience at commercial nuclear power plants to date has shown that the average gross activity of liquid effluents during routine operation is generally less than 5 pc/1, or a factor of 20 below the AEC limit.

For air, the regulations generally apply at the site boundary, after an allowance for atmospheric dilution from monitored stack discharges. If either the identity or the concentration of any radionuclide in the diluted discharge is not known, the gross activity of the gaseous mixture cannot exceed 0.04 picocurie per cubic meter (pc/m^3) on a yearly average. If it is known that alpha emitters and certain beta emitters of improbable occurrence are not present, the gross radioactivity of the atmosphere at the site boundary can be as high as 10 pc/m^3 on a yearly average.

Operating records for existing PWR and BWR plants indicate that the radioactivity of gaseous stack discharges seldom exceeds one percent of the established limits. Offsite monitoring by utilities and by state and federal agencies indicates that there has been no detectable increase in atmospheric radioactivity or fallout that can be attributed to any commercial nuclear power plant.

Many plants and animals have the ability to concentrate specific radionuclides in certain organs or tissues. Iodine, for example, is concentrated in the thyroid of higher animals, silicon in the tests (external covering) of diatoms, calcium in the shells of mussels, strontium and phosphorus in the bony skeletons of vertebrates, and cesium in soft tissues. Concentration factors in excess of 500,000 have been reported for specific elements in some aquatic and marine organisms; but fortunately, reconcentration reaches a higher level in lower plant and animal forms such as bacteria, protozoa, and phytoplankton than in

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higher forms such as vertebrates. There appears to be an inverse correlation between the complexity of body structure and the concentration of a specific radionuclide. In general, adsorption and absorption are governing mechanisms for the lower forms of life while ingestion is the principal route for predators.

It is conceivable, although highly unlikely, that the proliferation of commercial nuclear power reactors along a river or estuarine system, or on the shores of the Great Lakes, especially Lake Michigan, could result in reconcentration of radionuclides in aquatic or marine animals to the extent of causing a hazard to human health, despite the fact that each discharger meets the requirements of the AEC regulations. Extensive monitoring and evaluation of the Columbia River below Hanford and the Clinch River below Oak Ridge have revealed no cause for alarm to date, but the potentialities of the situation warrant continued careful surveillance.

ACCIDENTAL RELEASES

In the light of these facts it should be evident that normal operation of nuclear power plants will present no significant radiological hazard to air or water resources. But what about abnormal operation? What are the possibilities and the consequences of a serious accident?

A nuclear power plant cannot possibly explode as an atomic bomb because the ratio of fissile uranium to total uranium is far too low, because there is a high degree of moderation by the primary coolant and the control rods, and because the spacing of fuel elements within a reactor precludes a chain reaction fast enough to cause an explosion.

It is possible, however, for the multiplication factor (the rate of neutron production divided by the rate of their capture or escape) to exceed 1.000 for a period sufficient to cause a nuclear excursion that would lead to overheating of the core, to a possible meltdown of the cladding material, and to a release of fission products. A nuclear excursion might result, for example, from an environmental disturbance such as an earthquake, tornado, or seismic sea wave; from a failure of the complex and sophisticated instrumentation; from human errors; from deliberate sabotage; or from the sudden rupture of a pipeline or pump, which would discharge the primary coolant as steam and remove the moderator from the core.

The fission products held within the cladding of fuel elements in a 500 MW(e) reactor after 180 days of full-power operation have a total radioactivity of about 1.4 billion (10^9) curies. The discharge of all or a significant part of this activity to the environment might result in a serious hazard to the health and safety of the public, especially if the reactor is near a population center.

To forestall such an accident or to minimize its consequences, modern reactor design includes a series of engineered safeguards, generally with redundancy or backup. Systems are provided for spraying and/or flooding the reactor core in the event that a pipeline rupture causes a loss of coolant. Emergency diesel power is available to operate these systems if offsite power should fail.

If, in spite of the emergency cooling provisions, the core still melts and releases fission products, an added safeguard or backup system is available in the containment structure. This is typified by the huge dome that characterizes pressurized water reactors. The containment is designed to retain all gases and volatile fission products at internal pressures of 40 to 60 psi with a leakage rate of less than 0.1 percent per day, by volume. To assist in cooling and concentration of radioactivity in a containment, air recirculating systems with heat exchangers and iodine filters are provided. There are also containment spray systems with injected thiosulfate. For boiling water reactors the containment has the shape of an inverted light bulb, surrounded at the bottom by a torus, which acts as a pressure-suppression pool. Water is recirculated from the torus into the core spray systems.

The safety record to date of commercial nuclear power plants in the U. S. has been outstanding. There have been no deaths or injuries from radiation at any commercial power reactor. There have been no measurable effects of radiation on the public. Indeed, there have been no accidents at any reactors (commercial or research testing) that have been operated routinely at normal power levels. The only accidents have occurred at experimental test reactors at Los Alamos and at the Idaho test site where reactors are purposely put under heavy stress conditions.

The fact that the safety record to date has been exemplary does not mean that a serious accident cannot occur. In early 1968 the largest operating plants were only 462 MW(e) and 430 MW(e); yet several plants of 1,065 MW(e) are now under construction or planned. Although additional safeguards are being developed for the newer plants, the designs call for higher core power densities, and they utilize lower safety factors with respect to nucleate boiling than do the older plants. The increased power, the shortage of experience with large reactors, and the specters of human error and deliberate sabotage justify conservatism in the siting of nuclear power plants.

The populations within various distances of several existing and planned reactors in California are shown on the next page. Consider the consequences of an accident at San Onofre, with a resultant melting of the fuel elements and a release of steam and gaseous fission products within the dome-shaped containment. Consider also that aging for several decades, unequal settlement, corrosion, or small earthquakes have so weakened the containment that it leaks excessively (say 10 percent per day by volume) and that a gentle, persistent breeze is blowing toward the nearest population center. Even with a combination of these highly improbable adverse events, it would still be possible to prevent excessive radiation to the public because ample time and facilities would be available to evacuate the 20,000 to 30,000 people within ten miles of this reactor. Such effective evacuation was accomplished in about four hours just prior to the failure of the Baldwin Hills Dam in Los Angeles.

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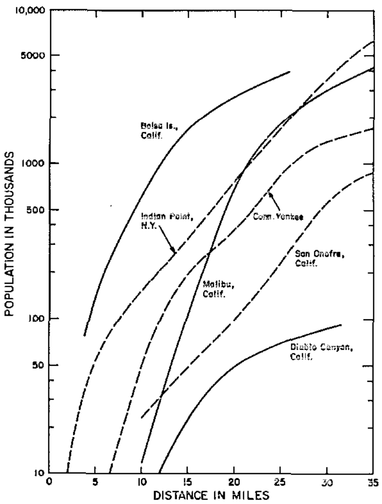

Populations within various distances of several existing (dashed lines) and planned reactors.

In contrast, consider a similar accident at the proposed site on artificial Bolsa Island near the metropolitan areas of Orange County and Los Angeles County. There the prevailing winds are onshore, and the population within ten miles approximates 600,000. Could this number of people be evacuated in six to ten hours, and if so where could they be housed for several weeks until they could return to their homes?

In addition to radioactive atmospheric contamination, a serious reactor accident could also jeopardize municipal water supplies if the reactor is situated on certain rivers or freshwater lakes. This impact might result from rainout of airborne particulate daughter products and/or from direct spillage of condensed steam and emergency core cooling water. About 30 miles upstream from Minneapolis, for example, a 472 MW(e) reactor is being built at Monticello on the Mississippi River. Every conceivable precaution is being taken to preclude the accidental discharge of radioactive liquids to the river, but if such an unlikely event should occur, the waterworks intake at Minneapolis would have to be shut down until the river had flushed all significant radioactivity past the city. Downstream communities would have to take similar precautions, although dilution and decay would make the problem less acute with distance.

Rivers have a fortunate facility for flushing themselves, but the replacement of water in many lakes may be almost interminable. The Great Lakes are especially vulnerable in this respect, and approximately 30,000,000 people depend on these lakes for municipal water supply. It has been estimated that the average retention time is 189 years in Lake Superior and almost 31 years in Lake Michigan. Moreover, the time required to remove 90 percent of a pollutant by natural flow is about 500 years for Lake Superior and 100 years for Lake Michigan. At the present time, ten large nuclear power plants are under construction or being planned on the shores of Lake Michigan. If any one of them should ever have an accident and release millions of curies of mixed long-lived fission products to Lake Michigan, the impact on this water resource would be catastrophic.

THERMAL CONSIDERATIONS

The efficiency of a steam-electric-power plant for converting heat energy into electric power is generally in the range of 30-40 percent. The remaining 60-70 percent of heat is dissipated into the environment. At fossil-fired plants (about 36 percent efficient) some of the waste heat escapes to the atmosphere through stacks, but most of it is discharged by means of the condenser cooling water. At modern nuclear-fired PWR and BWR plants (about 32 percent efficient) almost all waste heat is dissipated to surface waters through the condenser cooling circuit. Hence, although all steam-electric-power plants discharge heat to the water environment, the abnormal enthalpy (total heat) modifications from nuclear power may be expected to be greater than those from fossil-fired plants.

Consider, for example, the nuclear station being built in Minnesota. The rated electrical output is 472 MW, but the thermal capacity is 1,675 MW; hence about 1,200 MW will be discharged to the Mississippi River. The maximum flow of condenser cooling water will be 25.2 cubic meters per second, from which the temperature rise in this cooling water is calculated to be 11.4°C.

The river upstream from the Twin Cities can hardly be called the "mighty Mississippi." In fact, about 8 percent of the time the river discharge is less than the rate of flow through the condensing circuit of the power plant. For the average discharge of the river the temperature rise is calculated at 2.2°C, and for the minimum 10 percent flow, it will be 9.2°C. During summer months, this rise will cause the temperature of the river to exceed the upper limit of 33°C considered tolerable for game fish. Hence, the power company is planning to install cooling towers for use during warm weather and periods of low stream flow.

Are such modifications in enthalpy likely to be deleterious or advantageous to natural waters? The answer varies widely with the beneficial use to be made of the water, the season, the location, and many other factors. On the favorable side, for example, increased water temperatures may improve navigation in traditionally icebound rivers or harbors, lengthen the bathing and recreational seasons in cold climates, and favor the spawning of oysters. On the other side of the ledger, higher temperatures of water diminish its absorptive capacity for dissolved oxygen while simultaneously increasing the rate of oxygen metabolism and respiration by fish and other biota; accelerate corrosion; decrease the effectiveness for subsequent downstream cooling; enhance the toxicity of many substances; prevent the hatching of trout and salmon eggs; and, when sufficiently high, cause the death of some species.

It is generally considered that the deleterious effects from upward modifications of enthalpy outweigh the potential benefits, although these factors must be evaluated at each location and at each time of year. In any event, it is certain that average temperature change of 1.0°C or even less will have a major long-term impact on the ecology of nearby surface waters. Almost every action taken by man—indeed even his very existence—produces an ecological syndrome. Insofar as possible, these changes should be anticipated, evaluated, and optimized to the benefit of all mankind.