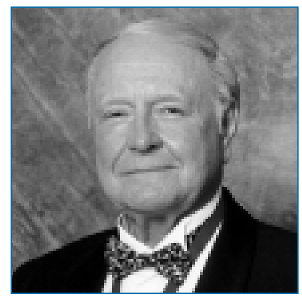
1996 Clarke Lecture

Fit Water for the Future: The Requisite Exercise of Social Discipline, Competent Technology, Responsible Engineering, and the *MEAD AORTA Agenda*

Walter J. Weber, Ph.D., P.E., D.E.E.
The Gordon M. Fair and Earnest Boyce Distinguished University Professor
The University of Michigan
Ann Arbor, Michigan



It is a singular honor for me to have been selected for the 1996 Athalie Richardson Irvine Clarke Prize. In accepting it, I am quick to acknowledge that no single accomplishment cited in support of my selection was single-handedly attained. I have benefited immensely from the rich intellectual environments in which I have pursued my efforts, and from the challenges and council of the wise mentors, supportively competitive peers, and bright students with whom I have shared the excitement and rewards of learning. I applaud the challenge for excellence advanced by Athalie Richardson Irvine Clarke, and the recognition that she, the Clarke Foundation, and the National Water Research Institute (NWRI) have provided in its support.

As I share with you today my pleasure in this magnificent honor, I share too my intent to present the substantial monetary award that goes with it to the University of Michigan for the purpose of initiating an endowed Environmental Engineering Excellence Fellowship. Michigan alumnae and alumni in the audience may expect to hear soon from the University, inviting you to help build on this beginning.

My Rime

In titling his 1995 Clarke Lecture, my distinguished colleague Dr. David White invoked, with appropriate editorial license, the lament of the Ancient Mariner.[1] In the spirit of resource reclamation and reuse (a concept central to the message of this lecture), I take editorial license of my own to put a different spin on the *Rime*; to wit, *Water, Water, Everywhere, Ours to Keep Fit to Drink*. Like Dr. White, it is an awareness of the expanding needs of modern civilization for life-supporting freshwater that prompts my parody of Coleridge, but my *Rime* more implores action than deplores condition. Today, I take this bully pulpit, as Dr. White called it, to advocate four specific, parallel, and coordinated courses of global action to ensure in the future that water is fit to drink.

The first and second courses of action I advocate call upon responsible stewards of our environment to combine their most urgent and earnest efforts to curtail the spiraling demands of society on the fixed resources of the Earth, specifically here with reference to water. The two distinct courses of action I envision as required to do this are each designed to reduce the corpulence of our society, and are each rooted in the exercise of *social discipline*. Our first course of action must be to re-evaluate and recalibrate our concepts and practice of economic and industrial development. The second

Dr. Weber is recognized internationally for his seminal work on the development of advanced technologies for water treatment and concepts for ensuring potable water sustainability. He founded the Great Lakes and Mid-Atlantic Hazardous Substance Research Center and the National Center for Integrated Bioremediation Research and Development, both supported by the U.S. Environmental Protection Agency, U.S. Department of Defense, U.S. Department of Energy, and several major industrial firms.

Over the past 40 years, Dr. Weber has authored or co-authored four books and over 300 peer-reviewed technical and scientific papers, and has mentored more than 65 Ph.D. graduates. Among his honors, he was named a Diplomate in the American Academy of Engineers in 1975 and elected to the National Academy of Engineering in 1985. Currently, he is the Gordon Maskew Fair and Earnest Boyce Distinguished University Professor at the University of Michigan at Ann Arbor.

requires that we address the eventual reality that, even if such development is placed on absolute hold, the cumulative resources of the Earth are insufficient to sustain indefinitely our current rate of human population growth.

The third and fourth courses of action are rooted in the application and refinement of *competent technology* and *responsible engineering*. The first of these is to implement with due haste and to our fullest ability the most effective and efficient technologies and schemes that currently exist for the purpose of co-current protection of the quality of our water resources and alleviation of current shortfalls in supply. Fourth, and finally, it is inevitable that we must undertake a *focused scientific agenda* designed to advance our scientific capability with engineered systems to complete the water cycle more aggressively and effectively than is done by this planet's intrinsic hydrology. My use of the first person plural in spelling out responsibility for the above actions refers to all of the peoples of the world, to the institutions that lead them and presumably serve their welfare, and most certainly to all of us who consider ourselves responsible stewards of the environment.

On occasions as heady as this, I am sometimes given to poetic — as well as editorial — license. It is in this vein I suggest that, as the body of every living creature repurifies and recycles its life-sustaining fluid, *blood*, a responsible global society must be prepared to so do with *water*, its life-sustaining fluid. Waxing further, I tighten the analogy between blood and water by drawing reference to *mead*, water enriched by the uplifting essence of fermented honey and frequently supplemented as well with manna, the divinely supplied nourishment of the Israelites. Given a draft or two of such brew, I might even liken our responsibility for distribution of fit water to society to that of the *aorta*, the artery that distributes blood to our cells, organs, fat, and muscles. This is the sense of my fourth mandate for action: implementation of the *MEAD AORTA Agenda*.

Curtailment of the Demand Spiral

Unsustainable Development

The term *to keep* in my *Rime* is meant to convey the act of preserving, or *sustaining*, which in turn is invoked as an adjective in several mantra around which we are regularly asked to rally. It is axiomatic, however, that problems will arise whenever the *sustaining* of one thing that we *think* is good for us or for society compromises our ability to *keep* another that we *know* is necessary. This is most certainly the case when what we seek to sustain is rampant development, while what we seek concomitantly to keep is fit water to drink. The sustaining of development as it is now practiced is an ultimate threat to our ability to stay ahead of a tidal wave of global entropy and, thus, to our ability to sustain an acceptable environment.

Unfortunately, sustainable development is a readily marketable mantra in today's world, linked as it is in the minds of most with better, more prosperous, and more comfortable lives. Conversely, arguments in support of sustainable environments, while broadly embraced in concept, offer less tangible immediate benefits and, therefore, tend to be viewed altruistically.

Issues of sustaining development *vis-a-vis* keeping water fit to drink are not simple matters of technology. Rather, they revolve about perceptions and related expectations of what technology can and should do for us, and what we are in turn obligated to do for ourselves. Such perceptions and expectations vary in specific detail from one part of the world to another, as thus does any redress of them required to correct deviations from reality. Globally, however, they are hardly anywhere now in concert with reality, and substantial changes in social discipline and responsibility are most assuredly necessary on a broad scale. The sustaining of an acceptable environment will require that society understand and accept totally new economic and lifestyle paradigms designed to slow resource demand spirals. There are probably few, if any, among us who would like to see the glutinous developments of the past perpetuated in the future.

Development as it is now practiced is a process that involves monotonically expanding resource consumption. Ours is an unsteady-state world in which such a process is simply not sustainable. The only condition under which development can be tolerated on an ongoing basis is if that process can be continuously recalibrated and adjusted to address and redress the changes it affects in the environment's ability to support it. The unsteady nature of the world and our environment can be illustrated by a simple but instructive application of material balance concepts to the behavior of any critical component (e.g., air, water, food) of an environmental system.

For most components critical to sustaining the environment as we know it, the first term on the right-hand side of the material balance relationship is essentially zero, and the second is small, at least in the context of a global *system*. One or both of these first two right-hand terms can, of course, assume large values for smaller subsystems (e.g., continental, national, regional) of a global environment.

A balanced global environment is one in which the last two terms on the right-hand side of the equation are approximately equal, and in which the left-hand term is, therefore, approximately zero.

This represents perhaps the most common, and most flawed, perception of sustainable development; that is, the controlling of *generation* and *consumption* to produce a *balanced environment*, a *steady-state system*. It does not represent the reality of what is practiced in the name of sustainable development.

Were it possible to control the last two terms in the above equation simply by applying appropriate technologies, the tasks before us would be reasonably manageable. Unfortunately, it is a simple fact that technology alone cannot control the steadiness of our *system*. Indeed, technology in general — and most particularly what we normally consider *environmental technology* — may provide no more than a means by which to delay the eventual demise of development as now practiced.

Those who argue for sustaining development commonly expect the action to translate into the achievement of a living standard like that of the most economically developed nations of the world; this is an unrealistic expectation. The most economically developed countries of the world have, in most cases, gained that status by placing disproportionate and inappropriate stresses on our planet's resources. The resources that remain are not likely sufficient to support similar levels of development on a global scale, at least not if attempts to do so involve the errors and inefficiencies of past development efforts.

Action Item 1. *Earnest efforts must be made at broadly international levels to devise and implement political, social, and economic means to bring rampant ill-considered economic and industrial expansion under control. It is the environment that must be sustained, not development, as now practiced.*

Unsustainable Population Growth

The greatest impediment to balancing the last two terms of any global material balance relationship is the fact that *consumption* and *generation*, while both functions of the size of populations, are unequally so. History and the factual evidence it provides us form a strong basis for arguing that as populations increase, so to do ratios of *consumers* to *producers* and of *consumption* to *production*.

The reason for the evident historic divergence of development and net productivity (production minus consumption) is quite simple. The resources of the world are roughly fixed; that is, on spatial and temporal scales of global magnitude, the first two terms on the right side of the material balance equation are roughly equal and their difference is, therefore, close to zero. The first resources used are usually the easiest to secure, and the recycle of resources is no less beset by problems of entropy than is any other action on Earth. Thus, unless *per capita* consumption continually decreases, or more efficient technologies for the production and recycling of resources evolve rapidly and continuously, the ratio of consumption to production must increase with increasing population.

It is unlikely that current and developing environmental technology can keep apace of the growing consumptive demands of our global population, at least if population expansion continues its current behavior. To illustrate the population growth problem, consider these few simple facts drawn from respectable sources[2,3]:

- The human population of the world increased about *four-fold* to approximately *1 billion in the 18 centˇˇˇˇs* preceding the industrial revolution of the nineteenth century.
- The population *doubled to 2 billion in the 130 years* between 1800 and 1930, *increased to 3 billion by 1960*, to *4 billion by 1974*, and to *5 billion by 1987*.
- At its current rate of growth, the world population will exceed *6-billion people 4 years from now*, and over *400-trillion people six centuries later*.
- It has been estimated that there will be *standing room only* on the surface of the Earth *by the year 2670*.

Parenthetically, if the latter projection holds true, I rather expect the rate of population growth to slow a notch or two after 2670.

The realities associated with such population explosions are that available lands throughout the nations in which the growth is heaviest are being rapidly degraded, thus reducing capacities for food production. Per-capita food production in Africa, for example, has declined by approximately 20 percent in the past

Net Accumulation or Depletion of Critical Component Within the System	=	Flux of Critical Component Into the System	−	Flux of Critical Component Out of the System	+	Generation of Critical Component Within the System	−	Consumption of Critical Component Out of the System
Zero Only for Steady State		*Zero for Fixed Resource Base*				*Zero for Sustainable System. Negative for Unsustainable System*		

25 years.[4] As a direct result, larger numbers and higher percentages of the peoples of Africa now have insufficient supplies of food to sustain healthy and productive lives. In Asia and Latin America as well, people are increasingly becoming *both victims and agents* of environmental deterioration, forced to destroy their ecologies and natural resource bases simply to stay alive. Seeking relief from such life-threatening declines in local resources and productivity, millions have emigrated from rural environments to cities and other urban areas, overburdening the water supply and pollution control capabilities of the infrastructures of those urban areas to the point of threatening human health.[5,6]

In the face of uncontrolled population growth, and in the absence of some unforeseen and unforeseeable scientific discovery, technology cannot as it currently exists maintain a balance between the last two terms of the global material balance equation for any one critical component, let alone all components of environmental concern; nor in fact can new technology be developed sufficiently fast enough to do so. From a totally pragmatic point of view, advanced technologies — even if they evolve and mature rapidly and continuously — cannot be implemented to improve and expand required urban infrastructures rapidly enough to keep pace with the demands of uncontrolled population growth.

Simply to maintain the qualitative *status quo* of their water supplies, sewerage systems, and pollution control measures, most third-world nations will have to expand their respective urban infrastructure capacities by approximately 60 percent *within the next 4 years*.[7] Even larger requirements for infrastructure investment exist in certain major urban areas of the world. The primary water and pollution control infrastructure for Mexico City, for example, was planned and developed in the 1950s, when the city had a population of about 3 million. By the end of this decade, the population of the greater Mexico City urban area will have increased to more than 25 million.[8,9] The original water and sewer systems of Cairo were installed at about the same time (1950s) for a population of 2.5 million people. It is expected that just 4 years from now, the population of Cairo will be more than 11 million.[(8,9)] The same conditions exist in New Delhi, which in approximately the same timeframe, will have increased in population by more than 10-fold to more than 13 million, and in Nairobi, which also in roughly the same timeframe, will have experienced a population explosion of almost 38-fold to a level of 5.3 million.[8,9] It is simply not economically or technically practicable to turn over infrastructure at rates sufficient to meet the demands of current urban population growth. There was a time when procreation was required for survival of the human race; to survive now may demand instead a global program of perceptive primiparity.

Action Item 2. *Humane but rigorously effective means must be devised to bring unbridled population growth into line with the capacities of our resource base. The quality of human life and, ultimately, the existence of humankind are threatened by socially irresponsible propagation.*

Technology in Perspective

Competent Technology

To introduce this part of my lecture, I offer a broad classification of technology according to major functions and applications with respect to safeguarding our natural aquatic resources.

- *Avoidance Technologies*: Those which minimize the manufacture and limit the production of substance that degrade our water resources (e.g., pollution prevention and waste minimization).
- *Control Technologies:* Those which remove or destroy potentially harmful substances before they enter the aquatic environment (e.g., industrial and hazardous waste treatment).
- *Remediation and Restoration Technologies:* Those that remedy existing cases of degraded aquatic environments and restore them to acceptable conditions (e.g., groundwater clean-up and wetlands restoration).
- *Monitoring and Assessment Technologies:* Those that are used to establish and monitor the conditions and overall "health" of our water resources (e.g., remote sensing and water quality effects modeling).

To be maintained in a competent state, all four categories of technology must be continuously and increasingly improved, integrated, and implemented in direct proportion to escalating water demands. There are numerous examples of how, in the past, we have found it necessary to systematically advance the competence of technologies in each of the above categories to maintain standards in the face of declining resources, or to contend with changes in use and consumption that have threatened those standards. Usually, however, we have been called upon to accomplish such advances only over limited spatial and temporal scales.

When I began my career some 35 years ago, it was still possible to find pristine sources of water in many urban regions of the world. Indeed, the majority of my mentors and preceptors — two of whom yet look over my shoulder as co-holders of my professorial title — held this was the *only* way to provide public drinking water. The technologies required to transform such resources into adequate supplies of acceptable quality for municipal and industrial use were relatively straight-forward. This was true even for development of such large and remote reserves as those of the Catskill and Quabbin reservoirs, which once served well the needs of two of the largest cities of the United States: New York and Boston, respectively.

We have witnessed serious degradation in the quality of most such resources in the intervening period, and the quantity demands placed upon these same resources have generally grown to exceed their supply capabilities. In several of the same urban areas in North America and Western Europe once served by such pristine resources, we have had since to reclaim and reuse sewage to meet the water supply demands of expanding populations, at least the non-potable elements of those demands. Pristine freshwater is simply no longer available in adequate supply on most of the Earth's continents. Increased use and intensified pollution have severely overtaxed the water resources of most regions of the world, and future demands for water must, in such circumstances, be met by more effective use of existing resources, regardless of their quality.

We have, in the past, been able to upgrade conventional technologies to render them competent of maintaining accepted standards in the face of declining source quality. It is reasonable to expect this level of response from our technology for some time into the future, at least with respect to the specific needs of certain regions of the world. It will be necessary, however, for us to be increasingly innovative in our efforts to refine existing technologies as needed to keep them competent and to be meticulously responsible in our engineering practice to ensure they are appropriately and effectively implemented.

Responsible Engineering

I have long held and vigorously maintained that one of the most reasonable solutions to the vexing problem of adequate and safe water resources lies in repeated reclamation and the direct and deliberate recycling and reuse of water. In short, once you get water where you need it, you have a valuable onsite resource. Given competent technology, that resource can be repeatedly reclaimed and recycled, supplemented only as needed from offsite sources to make up losses or meet increased demands. The treating of recycled water to high levels of quality is generally easier and less costly than transporting it over long distances, using it once, and thence disposing of it as waste. I have been convinced for some time that we must address the reality of a continuum of water quality, and the need for developing and implementing of technologies for transforming water of any quality along the continuum to any other quality required for a particular use. Our growing demands for water result in increasingly frequent short-circuiting of its normal hydrologic cycle, rendering superficial boundaries between natural waters, water supplies, and wastewaters more artificial than they have ever been.

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must be prepared to so do with water,
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At the most rudimentary level of reuse, farmers in arid regions of the world have reused untreated or modestly treated wastewaters for crop irrigation for as long as history has been recorded. Current reuse needs are, of course, more demanding in terms of both quantity and quality. I consider myself among the early, although not the first, to advocate more sophisticated means for water reclamation, and more extensive schemes for its reuse.[10,11] I am far from being its sole or most prominent proponent today. Professors Daniel Okun of the University of North Carolina at Chapel Hill and Takashi Asano of the University of California, Davis, have long advocated and spearheaded increased levels of practice and increasingly sophisticated means for water recovery, reclamation, and reuse. These two visionaries, and a handful of other *avant-gardists*, have led and continue to lead singularly effective campaigns for urban reuse of water for agricultural and recreational land irrigation, and for implementation of dual public water supply systems providing parallel supplies of potable drinking water and reclaimed water for non-potable use.

The Irvine Ranch Water District, represented on the Clarke Prize Executive Committee by Peer Swan, has implemented such reuse programs extensively. The Orange County Water District, represented on that same Committee by William Davenport and Langdon Owen, was early to implement innovative reclamation and reuse schemes, not only for urban irrigation, but for groundwater recharge as well, a use that eventually couples reclaimed water with potable water supplies. The individuals and agencies cited are part of an advance cordon of a growing legion of responsible proponents and practitioners of expanded water reuse. Countless examples of effective reclamation and reuse practice now can be found in virtually every corner of the Earth. I applaud the pioneers and encourage continued expansion of the practice.

I was considered a brash young man some 35 years ago for suggesting that advanced technologies would allow us eventually to completely reuse water. Sober audiences frequently took me to task, deriding such brazen concepts and, perhaps, even viewing me as a member of some radical fringe group. It was, therefore, particularly gratifying for me 3 months ago to attend a Water Reuse Conference sponsored by two of the most traditional and staunch guardians of water quality in the United States: the American Water Works Association and the Water Environment Federation.[12] In my mind, this conference, at which nearly 100 papers describing technologies for water reclamation and recovery and detailing examples of reuse practice were presented, heralds the wide-scale acceptance of reuse as an integral factor in water resource development and planning. Additional evidence that this is the case is the joint publication by the United States Environmental Protection Agency and the United States Agency for International Development of a strategic manual entitled *Guidelines for Water Reuse*.[13]

Building on the developments cited above, and acknowledging that the technologies employed and the efficiencies of the reuse schemes invoked must be fully competent, I suggest it is a matter of responsible engineering that we vigorously pursue a third parallel course of action.

Action Item 3. *It is imperative that we implement, in a timely manner and to our fullest capability, the most competent technologies and reuse schemes available to co-currently protect our water resources and alleviate overtaxing demands.*

Impending and Future Needs

Of the nearly 100 papers presented at the conference cited earlier, none were quite bold enough to claim an ultimate solution to the lament of the Ancient Mariner. The ultimate stumbling block lies in the verb *drink*.

It is one thing to refresh your lawn with reclaimed water and quite another to imbibe it personally. There are legitimate reasons, both psychological and scientific, for our natural reticence to complete the ultimate hydrologic cycle. Nonetheless, others have done so of necessity before us and have survived, and we must recognize the ultimate necessity to do so as well, but also to do so better. There are, in fact, extant circumstances of *defacto* potable use of reclaimed water that we find quite acceptable. A local case in point is Orange County, California, where reclaimed water used to recharge groundwater resources ultimately serves as a source of supply.

Psychological barriers to complete water recycling might be lowered if we replace references to *reclaimed* with such terms as *previously drunk*; that approach seems to work well in some cases, particularly with respect to expensive used automobiles. A more rational and scientifically sound approach is to advance the level of our technology for reclaiming and repurifying water to the point of *absolutely ensuring it is fit to drink*. I plan shortly to advocate a specific and focused agenda for doing this, but let's consider the issue of underlying technology requirements first.

There are basically two ways one can deal with constituents of water that are problematic with respect to complete recycling. One is to *remove* them completely, and the other is to *destroy* them completely. From a strictly technical perspective, this can be done with absolute confidence using technologies readily available to us today. I would have no reservation, for example, about drinking on a regular and prolonged basis an effluent from an existing tertiary wastewater treatment plant after it were treated further by distillation. I might choose to add a few touches of sodium and calcium bicarbonates, but that is largely a matter of taste. Friends and associates I know from certain parts of the country might chose to spritz it instead with a bit of ferrous sulfide; taste is, after all, a matter of experience and conditioning.

What, then, is the problem? As usual, the devil lies in the detail — in this case, that of economics. The process of distillation, for example, frontally attacks an average specific heat capacity of water of 4.184 Joules per gram-°K, and a heat of vaporization of 2.26 kilo Joules per gram at 100°C. To distill 1-million gallons of water per day, enough to meet the total daily demand of only approximately 5,000 people in an industrialized country, thus requires approximately 9.3-billion British Thermal Units (BTUs), or 2,725 mega-watt-hours, of energy.[14] Distillation, and arguably other existing technologies that might be considered wholly competent of repurifying water for unrestricted reuse, are not economically feasible on a global scale.

I alluded somewhat poetically at the outset of this lecture to the *MEAD AORTA Agenda*. I suggest now in the context of this agenda, and in a much less poetic sense, a *suite of specific technologies* having particular promise for eventually eliminating all psychological, scientific, and economic reasons for not completely closing the water cycle. This *suite* includes *adsorption* and *membrane technologies*, both of which are competent means for *separating* a broad range of undesirable constituents from water. For the *destruction* of other undesirable constituents, I recommend *advanced oxidation technologies*, specifically those involving hydroxyl-free radical reactions.

Allow me first to emphasize that the convictions expressed in this section of my lecture regarding specific technologies are not recently developed. Rather, they are deeply rooted in early efforts in the late-1950s and early-1960s as a doctoral student researching the science of adsorption processes and their potentials for achieving advanced levels of waste treatment and water reclamation for reuse. These convictions were reinforced in the several years of exposure to reverse osmosis technology gained working as a consultant with General Atomics and its successor, Gulf General Atomics, while a young professor at Michigan in the late-1960s and early-1970s. My interest and exploration of free radical reactions began at about the same time, starting with research on the use of ozone as a reagent for the destruction of aromatic compounds in advanced waste treatment and, subsequently, on the use of free radical reactions for reducing levels of trihalomethane precursors in drinking waters and destroying highly recalcitrant organic constituents in hazardous wastes.

We like to think we are at the cutting edge of technologies for purification of water and, for the most part, we are. It is sobering to note, however, that as early as 1930, the City of Los Angeles operated a 200,000 gallon-per-day reclamation plant for recharge of groundwater.[15] The plant employed activated carbon adsorption and was said to produce "…drinking water which is void of suspended solids, oxygen demand, odor, taste, color, or smell, meets drinking water standards, and costs less than untreated water brought in from outside sources." Adsorption still stands today as a "backbone technology" for water purification at all levels of water quality anywhere along the spectrum. The technology has become increasingly competent over the years as a result of efforts to improve our understanding of the process itself and, thereby, to learn how to improve the adsorbents and reactor schemes in which we employ it for water treatment. There is room, nonetheless, for further improvements and higher levels of competency, particularly with respect to the development of new adsorbents and the interfacing and integration of adsorption technologies with complementary membrane separation technologies.

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Membrane technologies, and certain advanced adsorption technologies as well, have just begun to blossom to full potential as a result of advances in polymer science over the past two decades. A membrane process is one in which selected components of complex mixtures are subjected to spatial energy gradients, but constrained in their attempts to respond to those gradients. The membrane is the constraint, and the gradient can be the result of any one or more of a large number of potential energy differences across it.[14] The most simple embodiment of this concept is the separation of suspended solids by a membrane through which the suspending water flows under the influence of an hydraulic energy gradient (i.e., *ultrafiltration*). The beauty of the concept lies in the remarkable range of different types of energy gradients that can be employed, and the number of different constraints or barriers that can be devised and built to effect highly selective and efficient separations. We have only begun to develop and employ the broad range of membrane separation processes that are possible.

I was intrigued, as a young researcher some 35 years ago, by the theoretical potential of membrane separation technologies. Frustrated with the limits imposed by the membranes themselves at that time, however, I turned my efforts to lower hanging fruits, specifically those associated with adsorption processes. I am delighted by the clear thinking evident in NWRI's identification of membrane research and development as a priority area for support.

Lastly, I urge concerted research and development of advanced oxidation technologies for destruction of the remaining undesirable constituents of recycled water, specifically technologies that can accomplish complete mineralization of organic entities (animate or otherwise) by free hydroxyl radical oxidation. The hydroxyl radical is a reactive intermediate formed, for example, when *ozone* decomposes in water. The addition to ozonation processes of *hydrogen peroxide*, a relatively inexpensive and readily available chemical oxidant, initiates the decomposition cycle of ozone, resulting in the enhanced formation of hydroxyl radicals. Oxidative destruction of compounds immune to ozone or hydrogen peroxide oxidation alone can often be achieved by supplementing the reaction with *ultraviolet irradiation*. Many organic contaminants absorb ultraviolet energy and are decomposed directly by photolysis, or become more excited and, thus, more reactive with chemical oxidants, such as ozone or hydrogen peroxide. In *photocatalysis*, ultraviolet radiation is used to excite a solid-state metal catalyst such as *titanium dioxide* and, thus, to speed up the process of generating hydroxyl free radicals. In an alternative approach to advanced oxidation, the irradiation of aqueous solutions with *high energy electrons* results in the rapid formation of excited state species *and* such reactive species as hydroxyl and hydrogen free radicals. In short, there is a broad range of different ways that free radicals can be generated in aqueous systems. This, coupled with the effectiveness of these reactive agents in destroying even the most resistant of organic species, ensures their future role in the *MEAD AORTA Agenda*.

I began this lecture by contriving an analogy between the critical fluids of the human body and the Earth: blood and water, respectively. I then drew a water-blood link to mead, and likened the responsibility for distributing life-sustaining fluids to the function of the aorta. In the title of the lecture, these analogies are further represented as comprising an *agenda*. Let me complete my circuitous poetic loop by explaining that the agenda I advocate is one involving a specific technology approach, an approach designed to move us into step with the realities of our water needs for the next century and beyond: specifically, the ***ME***mbrane ***AD***sorption **A**dvanced **O**xidation ***R***epurification ***T***echnology **A**pproach ***Agenda***.

Action Item 4. *As forward-looking and responsible stewards of fit water, we must work to ensure a robust institutional infrastructure that will aggressively promote the development and refinement of technologies that will allow us in the immediate future to complete the water cycle with absolute confidence*.

Closure

We stand on the threshold of the twenty-first century. Our hopes as a civilization for emerging from that century with a more livable environment than that with which we soon will enter are to be influenced largely by what we do now and in the first few decades of the 2000s.

I have expressed today what I think are legitimate concerns about our abilities to cope with the spiraling demands of society for water, particularly for safe, drinkable water. I have also advanced some strong personal convictions of what is needed to maintain and enhance the competence of technologies that can address the growing demands for water and the increasing difficulties of keeping it fit to drink. I question seriously, however, whether environmental technologies are now, or ever will be, capable of sustaining development of the type and magnitude we are currently experiencing and might, without vigorous redress, anticipate for the future. In its current concept of development, humankind is consuming the capital resources of the Earth at unsustainable rates. If changes in technologies cannot keep pace with growth and demand in the face of fixed global resources, then attitudes and management policies must be changed and paced to the limitations of resources and technology *if the quality of life is to be sustained*.

I am no apologist for technology. If the human race ultimately fails to sustain whatever it defines as desirable development, it will not be because technology has failed. Rather, it will be because the human race has depended too heavily upon technology and insufficiently upon sound judgment and social discipline. I hope that message goes forward from this lecture just as surely as do any of my messages regarding the urgent and judicious development and application of technology for fit water for the future.

I thank you sincerely for your warm and friendly reception. I appreciate your indulgence of my whimsical fancy in coining the *MEAD AORTA Agenda*, an agenda that I believe in very seriously. In parting, I trust that fit water will always be yours and mine to drink, to appreciate and cherish for what it is, and, of course, with our most earnest efforts to keep.

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