# Campaigner

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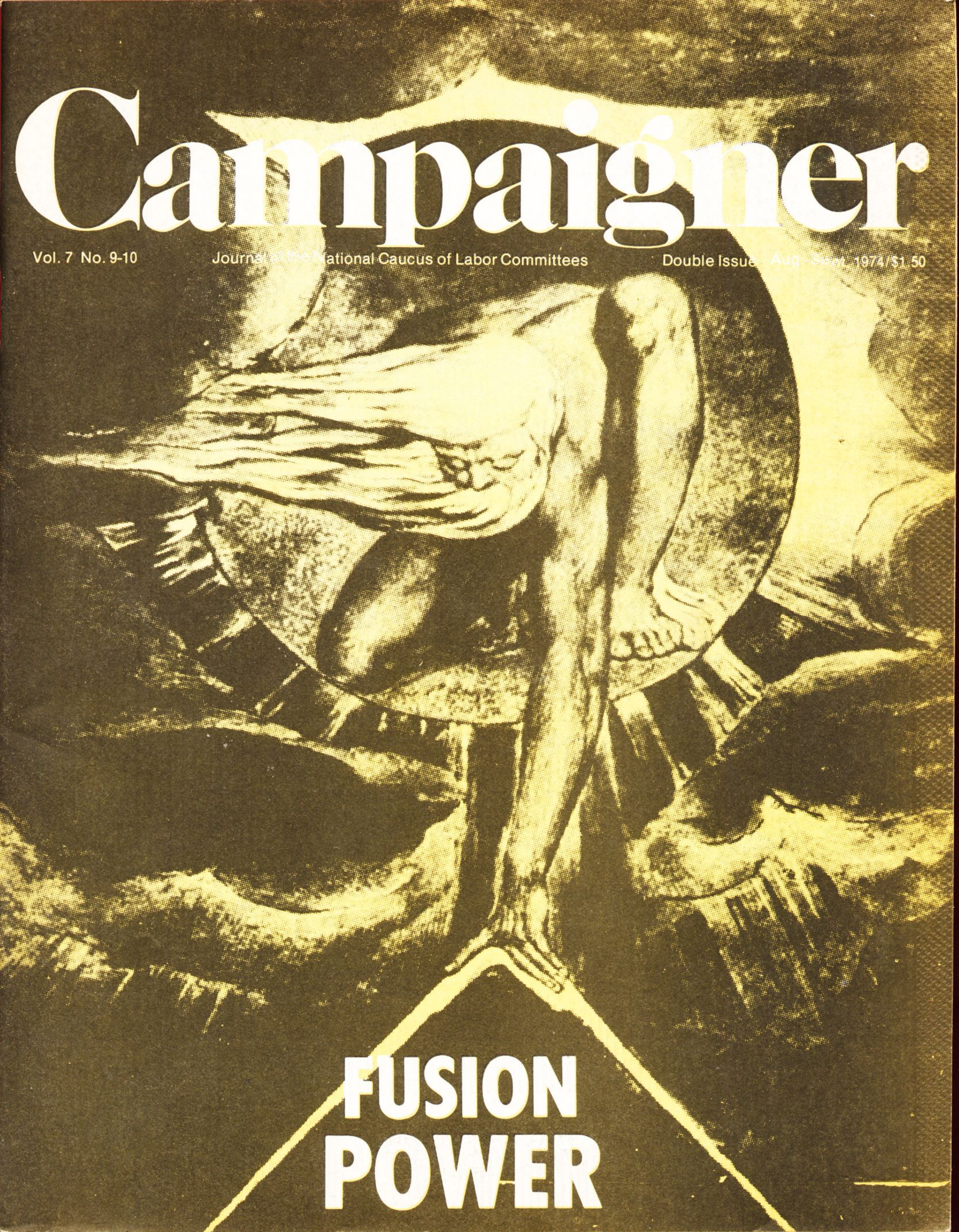

# FUSION POWER

On the cover of the **Campaigner** is the Creation by William Blake.

# the Campaigner

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# Forward

With the publication in this Campaigner issue of a number of substantive theoretical pieces and detailed proposals on the development of controlled thermonuclear fusion power and technology authored by leading physicists and engineering specialists, the National Caucus of Labor Committees further substantiates the immediate feasibility of a "Manhattan Project"-style crash program for the development of fusion power.

The extensive discussions held over the past months with virtually every leading researcher in the field (including those whose contributions are published in this issue) have shown that there is virtually complete agreement among these scientists that large-scale production of fusion energy could start in the early 1980's if a crash program were initiated now. In its first phase such a "brute force" development project would lead to the construction and operation of various parallel experimental units representing alternative, but not necessarily mutually exclusive, courses to the development of future large-scale production units. The first such units could actually be built before the end of the decade.

In contrast to this substantiation of our claims about the feasibility of a crash program, the United States Atomic Energy Commission (AEC) remains totally committed to a tokenist approach to fusion power. Despite the statements of various official spokesmen that the AEC is seriously committed to fusion power, such as that of Dr. H.P. Furth (co-director of the Princeton Plasma Physics Laboratory) at a recent conference, no move whatsoever has been made to expand the funding of the project to anywhere near the level required. In fact, the fusion research budget will be increased by only 10 per cent this year less than that needed to compensate for inflation. All attempts to portray any program funded on the present level as a serious,let alone a "crash" program are purely absurd attempts to defuse the pro-fusion ferment already generated by our efforts.

The publication of the material in this issue poses the question of the form of our present and expected future collaboration with scientists who are committed to fusion power development but who do not necessarily agree with us in their broader world outlook. This issue is particularly relevant in that the authors of the technical pieces published here arrive, in part, at interpretations and conclusions which are at variance with a Marxist view. In the context of the discussion of the development of fusion energy, or for that matter, of topics in mathematics and science generally,we see no reason to escalate such disagreements into full blown "ideological disputes." In fact, we are confident that close collaboration between us and the researchers committed to fusion development will of necessity lead them toward the adoption of the broader features of our world view. This confidence is based upon our knowledge that the development of fusion energy and technology constitutes the central aspect of expanded reproduction and that therefore, any serious extended commitment to such development either on the theoretical or planning and implementation levels will raise and demonstrate the validity of Marxian conceptions.

More generally, the development of fusion power directly poses precisely those theoretical issues that have to be attacked if any progress is to be made in the most advanced areas of mathematical physics i.e. the problem of the "unified field theory." We cannot deal with this point in detail here. However,the first article in this issue sufficiently indicates that the conception of expanded value (negentropy) — necessary for comprehending the development of the economy through the revolutionary changes in technology which will accompany the introduction of fusion power — lays the basis for the new energy concepts (analogous to expanded value) needed for the development of a unified field theory.

These broader issues of theoretical physics will be examined in depth in the immediately upcoming Campaigner issues which will include: a critical review of contemporary mechanics and relativity theory from the standpoint of the Marxian notion of expanded reproduction; and an evaluation of the contribution to the development of a Marxian view of the physical universe contained in Reimann's writings on infinitesimal geometry and Cantor's theory of transfinite numbers.

## Contributors

**Dr. Gerald L. Kulcinski** is Professor of Nuclear Engineering and Director, Fusion Feasibility Study Team at the University of Wisconsin. **Prof. Robert Conn**, also of the Wisconsin Nuclear Engineering Department, worked with Dr. Kulcinski in directing the design of the Wisconsin Tokamak fusion reaction system, UWMAK.

**Dr. William C. Gough** is a physicist who was until recently on the conceptual evaluations staff of the Controlled Thermonuclear Reaction (CTR) division of the Atomic Energy Commission. He is one the earliest and foremost proponents of the "fusion torch", the revolutionary concept of separation of materials in a high-temperature plasma.

**Dr. Louis Gold** has been a pioneer in high density plasma fusion research since his work on the Manhattan Project. He has worked at a number of leading scientific universities, such as Brooklyn Polytech and MIT, as well as government laboratories. His more recent attempts to develop fusion power are described in his article.

**Morris Beller,** et. al., are staff members of the Energy Systems Analysis Group at Brookhaven National Laboratory on Long Island. Their group is responsible for conducting comprehensive, long-range studies of energy and integrated economic development programs, including the fusion based transformation of basic industry.

**Fred Howard** is a graduate student in computer science at Yale Univeristy, working on fundamental computer design. He has extensive experience in the programming of calculations of the behavior of simulated plasmas in fusion machines.

**Eric Lerner** is a founding member of the NCLC who has contributed to its ground-breaking studies in global socialist planning.

# Announcing

### the formation of:

# Fusion Energy Foundation

G.P.O. Box 1901 New York, New York 10001

A non-profit foundation dedicated to the dissemination of information regarding this essential source of energy for the future of human existence; and to providing financial assistance to those individuals and institutions engaged in research toward the immediate development of fusion energy.

With the passage of the Energy Research and Development Agency Act (ERDA), and the transfer of the functions of the Atomic Energy Commission to ERDA, we have entered a new period. The new energy research and development program will center on coal technology, with the breeder reactor staying in first place as projected "new" nuclear technology.

It is therefore especially timely to bring together scientists, engineers, technicians, and other citizens who are vitally interested in the development of fusion energy as the keystone of future technological development and human progress.

# Human Ecology and the Science of Socialist Program

Eric Lerner

The present collapse of the world economy has destroyed the illusions of all but the most fantasy-ridden that there is any possibility for further human development under capitalism. In fact, the continued survival of capitalism and the continued solvency of the major financial institutions is premised on the immediate and rapid *de-development* of the entire planet. Production and consumption are to be slashed, millions deliberately worked to death, technology replaced with labor-intensive methods. Entire populations are to be wiped out, whole continents turned into deserts. The maintenance of debt-service demands the return of humanity to barbarism.

In order to carry out this program of de-development, the dominant faction of the capitalist class, the Rockefeller cabal, is attempting to establish a worldwide military dictatorship in the present year. As we have repeatedly pointed out, the main weapons the cabal is using in this attempt are not the tanks and guns of its armies, which in themselves are totally ineffectual, but rather psychological manipulation. The cabal is trying to get both its factional opponents within the capitalist class and the working population as a whole to *accept* the program of de-development as *inevitable*, to concentrate on finding some relative advantage within the context of that program.

The cutting edge of this psychological offensive is the ideology of Zero Growth. Zero Growth is simply the justification for the notion that human development is impossible. Once it is accepted that "resources are limited," the psychological foundations are laid for the acceptance of military-fascist dictatorships, for the acceptance of an economy of cannibalization. If resources are finite, then continued human survival is impossible. Depopulation is inevitable, since in a world of finite resources, any population *at all* represents "overpopulation." Reduction in consumption is inevitable, labor-intensive methods are desirable, since finite resources must be conserved.

The acceptance of Zero Growth means a psychological transformation which precludes any resistance to the cabal's assault. Positive unity of action around common interests becomes impossible. If resources are finite, then the birth of any individual is the loss of everyone else; the death of any individual is the gain of every other ("Now we'll have more to eat"). If the world is overpopulated, then my survival is possible only at the expense of humanity. It is this bestial mentality of Zero Growth which makes possible the imposition of fascist dictatorship.

The ultimate logic of Zero Growth is cannibalism. It is no coincidence at all that the head of the Club of Rome, Aurelio Peccei, chief advocate of Zero Growth, is also an exponent of cannibalism — capitalism's final solution to the problem of food and population.

In order to stop the Rockefeller conspiracy, in order to carry through a socialist transformation, the conception of a world of finite resources, the ideology of Zero Growth, must be obliterated. We must demonstrate that human survival and development are possible. On one level, this means the actual development of program, outlining the concrete, immediate steps which can and must be taken to ensure the continued survival and reproduction of humanity — the development of fusion power, the expansion of food production. This shows in a direct way the potentiality for breaking through the supposed "finite resources" of the Zero Growth world.

The mere stating of a program, the posing of the immediate steps to be taken, will in itself have a tremendous impact in breaking apart the Zero Growth environment. But by itself, it is not enough. Zero Growth can be accepted, at least implicitly, by millions of working people, because it is coherent with the normal, common-sense world outlook and self identity of workers under capitalism. To the extent that the worker views him or herself as a competitor with other workers for existing jobs, to the extent the worker views the world in terms of fixed social relations between individuals governed by an unchangeable "human nature," then the worker shares the basic worldview of Zero Growth reductionism. Even if such a worker passively *accepts* a program for world reconstruction, he or she will be unable to see the actual process by which such a program can be realized, or their own role in that process. The situation is even more acute with the petit-bourgeois, whose self conception is much more that of a parasite.

The entire reductionist worldview, from which Zero Growth logically derives, must be destroyed and replaced with one which actually identifies the real process of human development. This actual process of human development is based entirely on the increase in the creative abilities of human society as a whole, a creative ability which increases with the expansion of the population. The creative ability, and the very existence of every human being, rest directly on the productive contributions of the rest of humanity.

This standpoint implies a psychological outlook diametrically opposed to that of Zero Growth. Any increase in the population increases the ability of every individual to consume and produce; the death of any individual is a loss to all. Anyone else's hunger, disease, or impairment of creative powers, is my hunger, my disease, the impairment of my creative powers. This is the consciousness that forms the precondition for a socialist mass movement.

To actually create an accurate conception of the process of human reproduction, reductionism must be destroyed in its most well-protected bastion, that of the notion of the physical universe. We must be able to put forward a conception of the physical universe which is coherent with what we know to be the process of human development. We must therefore develop a dialectical science of human ecology, a science of man's development in the context of the rest of the universe. We must answer the question: "How is human population growth possible?".

Not only is such a human ecology necessary to form a consistent conception of human development, and to guide that development through socialist planning, it is a prerequisite for the advance of science generally. In essentially every branch of science today, the reductionist approach has led to a series of insoluble contradictions and paradoxes, a general stagnation of theoretical advance. The elimination of reductionism in the physical worldview, and the merging of the methodology of the physical sciences into that of a generalized anthropology, or human ecology, is the necessary first step away from the present sterility.

The germ of the necessary conception of the physical universe is contained in Marcus' notion of "negentropic" development. The present article will elaborate this basic notion and accomplish two interrelated tasks — to demonstrate that the empirical evidence provided by human and biological evolution absolutely contradicts the reductionist worldview, and to develop a conception of physical processes which is coherent with an understanding of human reproduction and development.

## I. What is Reductionism?

We begin by describing the main features of the reductionist worldview.

There are two basic, interrelated axioms in the reductionist conception of the universe. The first is that the universe consists of independent, elementary particles (such as atoms, nuclear particles, individuals, etc.) The second is that these particles are organized and interact according to a set of fixed relations, or laws (such as the law of gravity, electro-magnetism, nuclear forces, etc.). Essentially every branch of existing science is reductionist in that each is based on these same axioms — discrete particles and fixed laws. Physics is the study of the fixed laws of interaction of the "ultimate point particles"; chemistry studies molecular interactions; ecology studies the interactions of biological individuals and so on.

The fundamental axioms of reductionism necessarily imply a certain conception of the dynamics and development of physical processes and the universe in general. This conception is known variously as the law of increase of entropy, or the second law of thermodynamics. It states that the universe as a whole, or any system in particular always tends towards a stable or unchanging state, a state of *equilibrium*. An equivalent statement is that the rate of change of the universe or any system tends toward zero: the universe is running down.

This dynamic law is a necessary consequence of the fundamental axioms. Any system defined by fixed laws must have some state from which no further change is possible. Any small, random change in such a state will always lead to the return of the system to the state of equilibrium. A few examples will illustrate this.

Figure 1a shows the state of equilibrium for a system containing white and black particles and no long-range forces or laws of interaction. It is a random mixture — any small change in the system will not change the random state. Figure 1b shows the state of equilibrium for a closed system of repulsive forces — whose strength increases with decreasing distance — an equally spaced lattice. Here any small change will lead to an increase in the force in the opposite direction, leading to a return to equilibrium. Figure 1c illustrates the same equilibrium

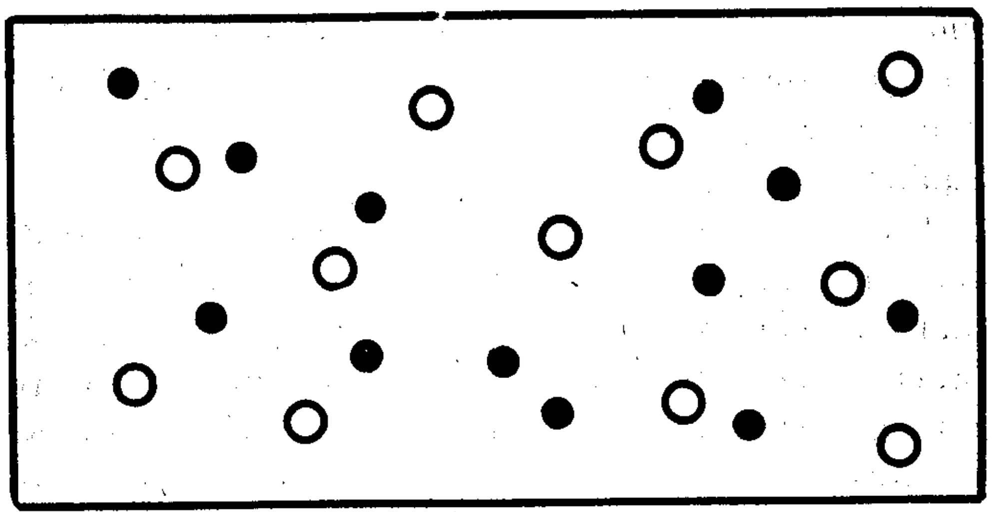


Figure 1a

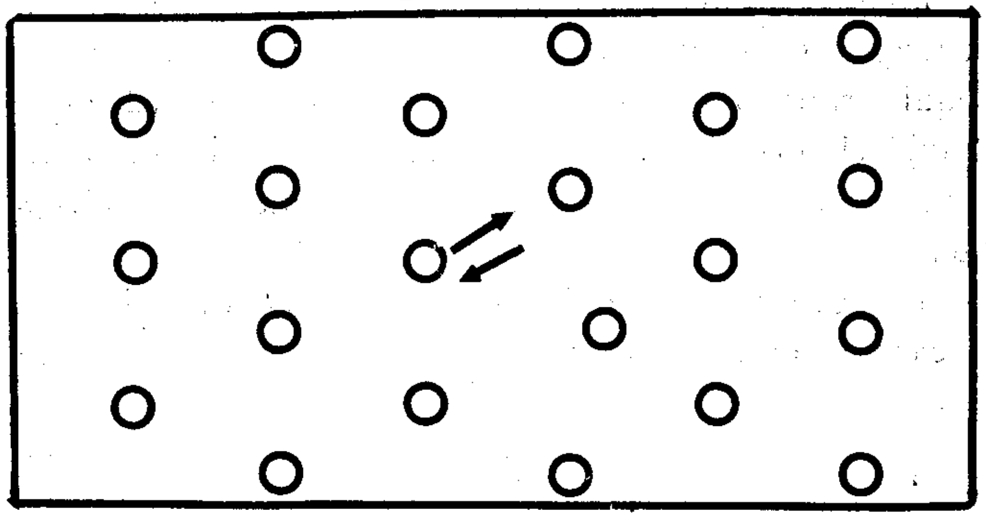


Figure 1b

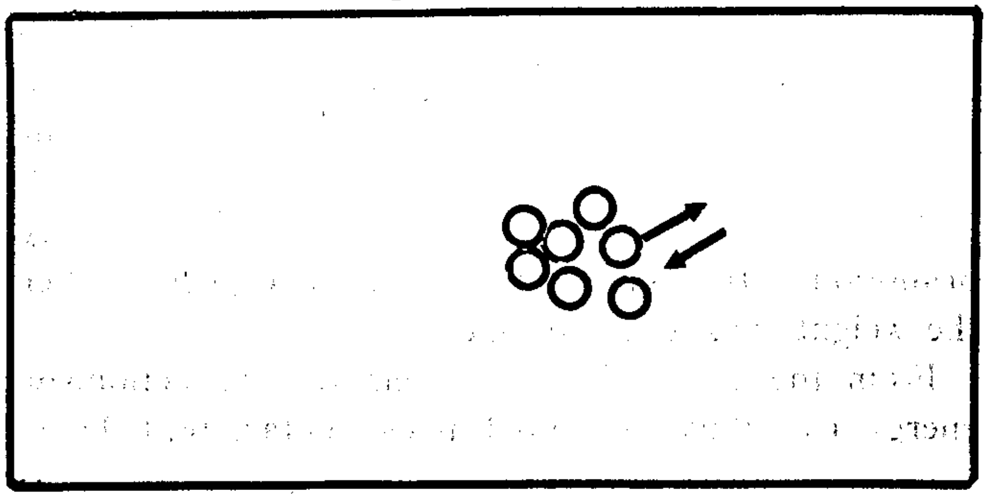


Figure 1c

state in the case of attractive forces — a total condensation of all the particles. Such equilibria can be determined for any combination of fixed laws.

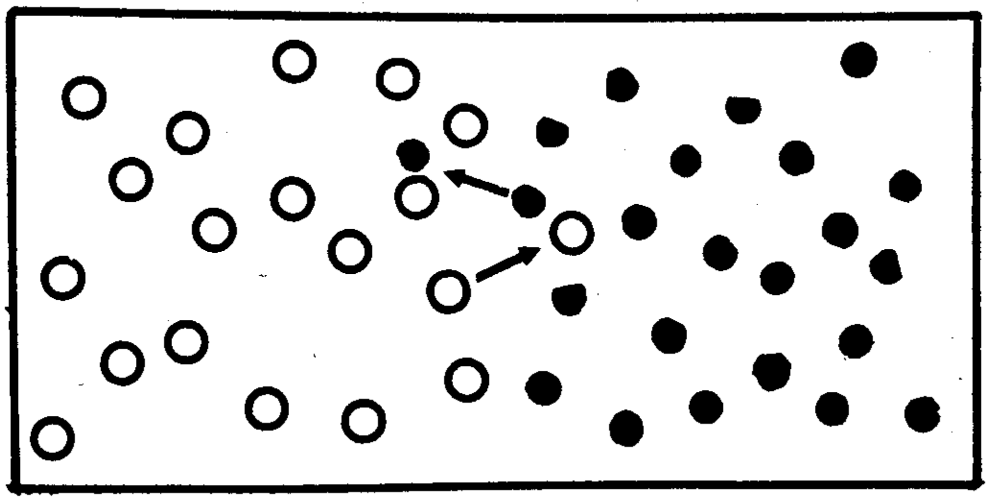


Figure 1d

It is equally necessary, given the axioms, that any system must approach equilibrium, or the state of no change. In a non-equilibrium state any random change in the state will lead, on average, to a more *probable* state and thus one closer to equilibrium, which is the *most probable* state. Thus, for example, any small change in the state 1d will lead to the mixing of the black and white particles, and thus towards the state of equilibrium in 1a.

The tendency of the universe towards equilibrium is at the same time a tendency towards increasing disorder and randomness, since disorder is more probable than order — that is, there are more possible states of random arrangement than ordered arrangement. This tendency towards increasing disorder is also called the increase of *entropy.*

Finally, the tendency towards a decline in the rate of change of the universe follows from its approach to equilibrium. While temporary fluctuations towards more rapid change are possible, as equilibrium is inevitably approached, the rate of change equally inevitably falls to zero.

This general conception of universal dynamics is most clearly formulated in the reductionist notions of *energy* and *potential.* If we assign to every state a number which indicates its distance from equilibrium state (the "potential"), then energy flow can be defined as the change in the universe produced by going from one potential to another. Thus a weight suspended 100 meters above ground level has a potential energy of 100 meters times the weight of the mass. When the weight falls to ground level, this amount of energy is "released," materializes in the form of "kinetic energy," the energy of motion of the weight, and is dissipated as heat when the weight strikes the ground.

From the standpoint of a consistent reductionism, energy itself must be viewed as elementary particles or "quanta." The release of energy through the change of potential is therefore conceived as the transformation and flow of such quanta — for example, the flow of energy from an electric potential field to an electric current, or the conversion of quanta of matter into quanta of energy in a nuclear reaction.

In terms of these notions, equilibrium can be defined as the state in which there is *no net flow of energy* — no change in potential. The total potential energy of the universe must be continually decreasing, and, as equilibrium is approached, the rate of change of the potential must drop to zero. The rate of energy flow in the universe must therefore also tend to zero.

A fundamental problem with the reductionist notion of a universe which is running down is how it ever got wound up in the first place. Generally, this embarrassing problem is banished from the field of acceptable scientific inquiry. The currently accepted cosmology, or theory of the origin of the universe, simply assumes that the universe suddenly "began" from nothingness as a state of high order, or *negentropy.* This intensely hot, dense gas rapidly expands in a primordial "Big Bang," and gradually cools into the present galaxies, stars and planets. Various sources of potential energy, thoughtfully provided to the universe at the time of Creation are in turn exhausted: gravitation is used up in the contraction of the stars, nuclear forces in the thermonuclear fusion processes which give energy to the sun and other stars, and in the end total equilibrium reigns.

A slight variation on this theme is contained in the competing "steady state" cosmology, which simply pushes the origin of the universe off to an infinitely distant past and reduces the rate of approach to equilibrium to zero.

In the context of such reductionist cosmology, the development of human society, and of life itself is clearly a mere temporary aberration in the general downward trend of universal evolution. Since the total potential energy is finite, any increase in the rate of flow of energy through the consumption by society of raw materials, food, and so on, must only lead to the more rapid exhaustion of potential energy and a more rapid approach to inevitable equilibrium.

In the case of living beings, a state of equilibrium, of zero net flow of energy, cannot exist, and therefore the inevitable tendency of the universe towards equilibrium means the inevitable extinction of man and life in general. Since human survival is impossible in the face of the inexorable rise of entropy, mankind faces the unenviable choice of cutting its consumption of the fixed supply of energy or negentropy and thus prolonging its existence, or continuing to increase its wanton consumption and dying off even earlier. Similarly, population and per capita consumption can be "traded off."

Nor can fusion power provide more than a mere postponement of the inevitable. Some of the more sophisticated advocates of Zero Growth have argued that the only difference between themselves and the position of the Labor Committees was the timing of the inevitable cessation of growth. For once it is accepted that the reductionist view of the universe is generally sound, then the growth of human society cannot proceed indefinitely — fusion power or no fusion power! Simple arithmetic will show that a 15 per cent annual rate of increase of energy production (about that required in the first years of socialist development) would lead to the total exhaustion of fusion power reserves in a mere 160 years. The *total* power of the sun (not just that falling on the earth) would be insufficient by the year 2200 and the power of every star within a sphere expanding at the speed of light would fail us within another century after that. The growth of energy and eventually population must cease. Rockefeller is right: Zero Growth is indeed inevitable.

A more serious question, however, is at issue here than the silly number games of the Zero Growthers. The reductionist conception of energy is, in fact, central to the whole notion of Zero Growth, and to the whole reductionist worldview. The self-admitted basis of all "finite resources" arguments is that energy is finite — the potential for change, therefore is finite. The central question posed, therefore, is whether an opposing conception of energy and thus of universal development can be put forward, one consistent with the continued existence of humanity? Or can we only state an immediate "practical" solution to the present crisis? It is this implicit question of worldview tied up with the question of energy which causes even worker-revolutionaries to be trapped by number games like the one just illustrated.

In fact, what should already be obvious is that we are here dealing not with a "scientific theory" derived from "observations" but with a metaphysic, an ideology. The fettering of scientific inquiry within the confines of this reductionist metaphysics has been an enormous factor in the current stagnation of physical and other sciences. A host of fundamental paradoxes arises out of the reductionist worldview. We mention merely the most important:

1) The origin of the initial negentropy and fixed laws of the physical universe is inexplicable within the confines of present physics and must either be ignored or attributed to a supra-physical agency. This view is in no way an advance on the "theories" of Creation formulated two thousand years ago by the authors of the Book of Genesis.

2) The conception of an elementary particle or "point particle" leads to a myriad of formal contradictions in the theory of electromagnetism and quantum dynamics.

Perhaps most glaring, reductionist metaphysics utterly excludes the phenomena of consciousness and produces the duality of mind versus body.

Most fundamental of all, reductionism fails completely to accurately describe the empirically-verifiable history of the development of the universe. Even a summary examination of a few sections of that history from the standpoint of thermodynamics is sufficient to absolutely discredit any reductionist notions of physical science. We now proceed to that examination.

## II. Thermodynamics of Evolution

The reductionist view predicts that a system will approach equilibrium and that the rate of energy flow, and more particularly the *rate of change of energy flow* through the system, must approach zero. In fact, any system which is studied as an entirety, rather than as an isolated sector, shows just the opposite tendency. The evolution of such systems is universally *negentropic*, steadily moving towards higher rates of energy flow and higher *rates of change of energy flow*. (We are here referring to energy as measured as collection of quanta — that is the reductionist energy familiar to any scientist or engineer.)

The actual history of human reproduction exhibits precisely this negentropic tendency.

The conception, touted by such once-reputable journals as *Scientific American*, that human population has remained virtually stagnant until the past two hundred years, that population growth is an aberrant recent phenomenon, is a simple lie. In actuality, not only has the whole of human history been characterised by accelerating growth, but so has all of organic and inorganic evolution prior to the existence of humanity!

As a first approximation, we can describe human social reproduction as a series of modes of reproduction, modes of relationship to the biosphere as a whole. We can characterize each mode by a certain characteristic pattern of energy throughput, a certain range of per capita energy flows, and a certain population and population growth rate. Table I illustrates the general succession of such modes of reproduction. The structure of energy throughput is shown in Figure 2.

The first mode is essentially pre-human. It is the simple gathering mode of the hominid populations existing over the period of approximately 1,000,000 BP (before present) to 100,000 BP. In this mode the hominid has at its disposal only the food energy which it can directly gather and consume.

The second mode, human hunting societies, (100,000-10,000 BP), is the first actually human mode, in which man begins to utilize the rest of nature as part of the reproduction of his species. Wood is used for fire, both

**TABLE IA**

| Year BP | Per Capita Energy | Rate of Growth | 2nd Order Rate |
|---|---|---|---|
| 1,000,000 | 2 | $2.0x10^{-5}$ | $4.4x10^{-6}$ |
| 100,000 | 5 | $.8x10^{-4}$ | $1.4x10^{-5}$ |
| 5,000 | 12 | $3.6x10^{-4}$ | $2.3x10^{-2}$ |
| 500 | 26 | $6.0x10^{-2}$ | $4.0x10^{-2}$ |
| 100 | 77 | $1.6x10^{-1}$ | |
| 0 | 230 | $1.5x10^{-1}$ | |

Table shows evolution of per capita energy flows. Time is shown in years before present. Energy in Kilocalories per day per capita, rate of growth as the ratio of growth of energy flow per generation to energy flow. Second order growth is the ratio of the per-generation growth in the *rate of growth* to the rate of growth. (The exponential notation indicates the order of magnitude of the number, thus $10^{-1}$ is equal to .1, $10^{-2}$ .01, $10^{-3}$ .001. and so on.

for heating and cooking. Improved hunting methods leads to increased consumption of meat, thus indirectly utilizing the larger food supply available to larger game.

The third basic mode is primitive agriculture, (10,000-5,000 BP), or barbarian society. A further and much greater increase in total solar energy utilized is made possible by the use of domesticated grains. This expanded energy is utilized in the form of animal power, as well as being consumed directly. The direct energy flow through human beings in the form of food becomes far less important.

The fourth mode, early caste and class societies (5,000-300 BP), includes the various distinct social forms of organization — Asiatic, ancient and feudal society — as sub-species of a single thermodynamic structure. In these advanced agricultural societies wind and water power are added and small but significant and growing proportions of the total energy flows are diverted to production of non-food goods — clothing, construction works, and metallurgy.

The fifth basic mode, a capitalist-industrial society (last 2-300 years), represents the most radical break. Agricultural energy as a whole becomes quite insignificant and fossil fuels provide the great bulk of the energy (in the case of fully developed capitalism). Only a tiny proportion of the energy is actually consumed by man directly, the vast majority going into various industrial processes, transportation, etc.

**TABLE IB**

| Year BP | Population (millions) | Rate of Growth | Second Order Rate |
|---|---|---|---|
| 1,000,000 | .125 | $6x10^{-5}$ | $9x10^{-6}$ |
| 300,000 | 1.0 | $8x10^{-5}$ | $1x10^{-4}$ |
| 25,000 | 3.3 | $4x10^{-4}$ | $3x10^{-3}$ |
| 10,000 | 5.3 | $1.4x10^{-2}$ | $-8x10^{-3}$ |
| 6,000 | 87 | $2.4x10^{-3}$ | $8x10^{-3}$ |
| 2,000 | 133 | $1.2x10^{-2}$ | $2x10^{-2}$ |
| 300 | 545 | $6x10^{-2}$ | $1.0x10^{-1}$ |
| 200 | 730 | $1x10^{-1}$ | $1.0x10^{-1}$ |
| 160 | 900 | $1.2x10^{-1}$ | $5x10^{-2}$ |
| 60 | 1,600 | $1.5x10^{-1}$ | $6x10^{-1}$ |
| 25 | 2,400 | $3.5x10^{-1}$ | $3x10^{-1}$ |
| 0 | 3,300 | $5.0x10^{-1}$ | |

Table shows evolution of human population. Population is in millions and the rate of growth of population and second order rate of growth are defined in Table IA. Thus, 25 years ago the rate of growth was 35% per generation and the rate of growth of this rate was 30% per generation.

We can add a sixth mode of socialist fusion-power-based society, in which the initial source of energy is not directly solar power at all, and a seventh mode of communist society, in which a large fraction of total solar output is utilized directly.

Table IA summarizes this succession of modes in terms of per capita energy throughput. There is an obvious, ever-accelerating increase in the rate of per capita energy.

The second column of the table shows the rate of growth of per capita energy. This is expressed as the ratio of the increase of energy consumption per generation to the total existing energy consumption per capita. This is thus a measure of the exponential rate of increase, or, of the *free energy* as a proportion of the total available. This free energy is a measure of that portion which is available for expansion, or "surplus" after the necessary amounts for maintaining the existence of the present population and their present reproduction is accounted for, and after further necessary deductions to maintain the productive environment (such as irrigation works, plant and equipment, etc.) are also made.

We find that this free energy ratio or rate of growth is itself growing, and is higher for each succeeding mode.

Further, the third column shows the per generation rate of growth of the rate of growth — the rate of increase of the surplus energy production. This too is increasing!

That is, energy flows increase, the rate of growth increases, (the rate of *surplus* energy production) and that increase is continually accelerating.

Thus we have an energy flow function of the form $e^{te^{bt}}$ where the parameter b is characteristic of the mode of production and itself increases in the course of social evolution as a whole. The characteristic time scale of evolution thus progressively drops from 200,000 generations to 70,000 to 40 to 25 as one mode succeeds another.

The same situation is reflected in the growth of population itself, as is shown in Table IB.

We see the growth of population in the first column. The second column shows the per generation proportional increase of the population — in other words the overall rate of expanded reproduction of the population. As in the case of rate of per capita energy increase, this reproductive ratio is a crude measure of the rate of social surplus, S/C+V, the ratio of labor available for expansion to that needed for maintenance of existing relations. This is in particular a valid approximation in the case of the early mode, in which the vast majority of the social surplus was realized in the form of expanding population directly.

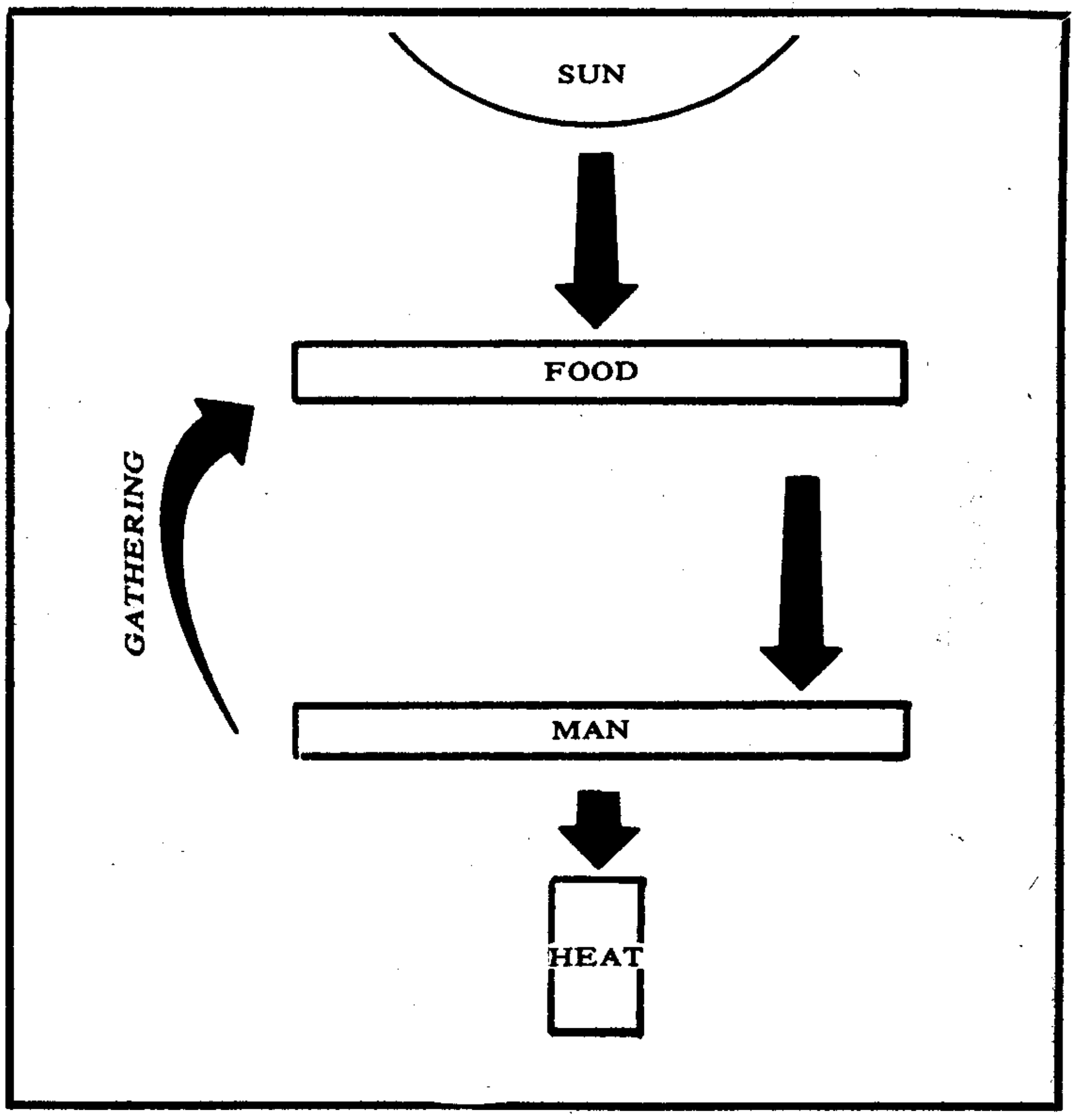
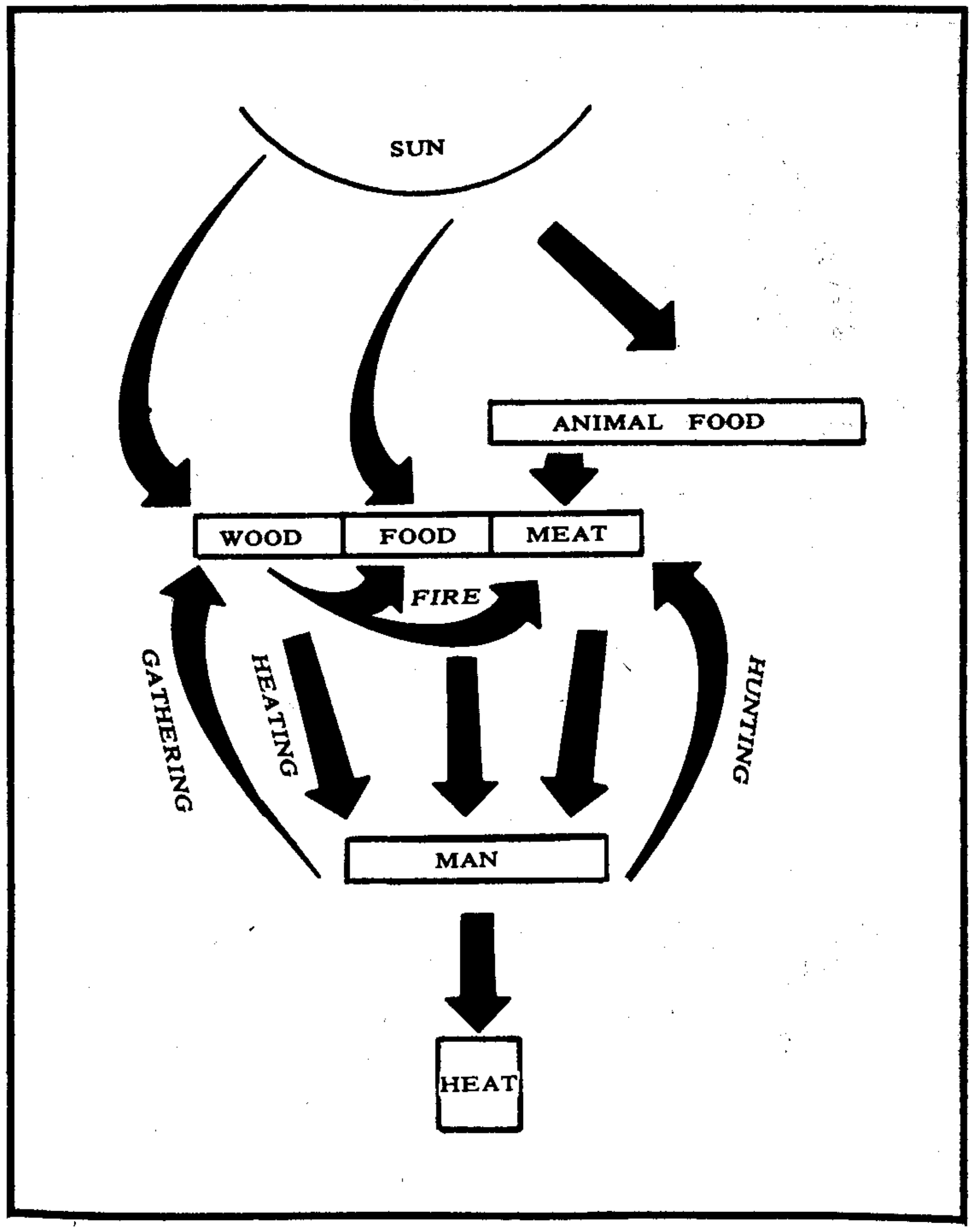


Figure 2a

Figure 2b



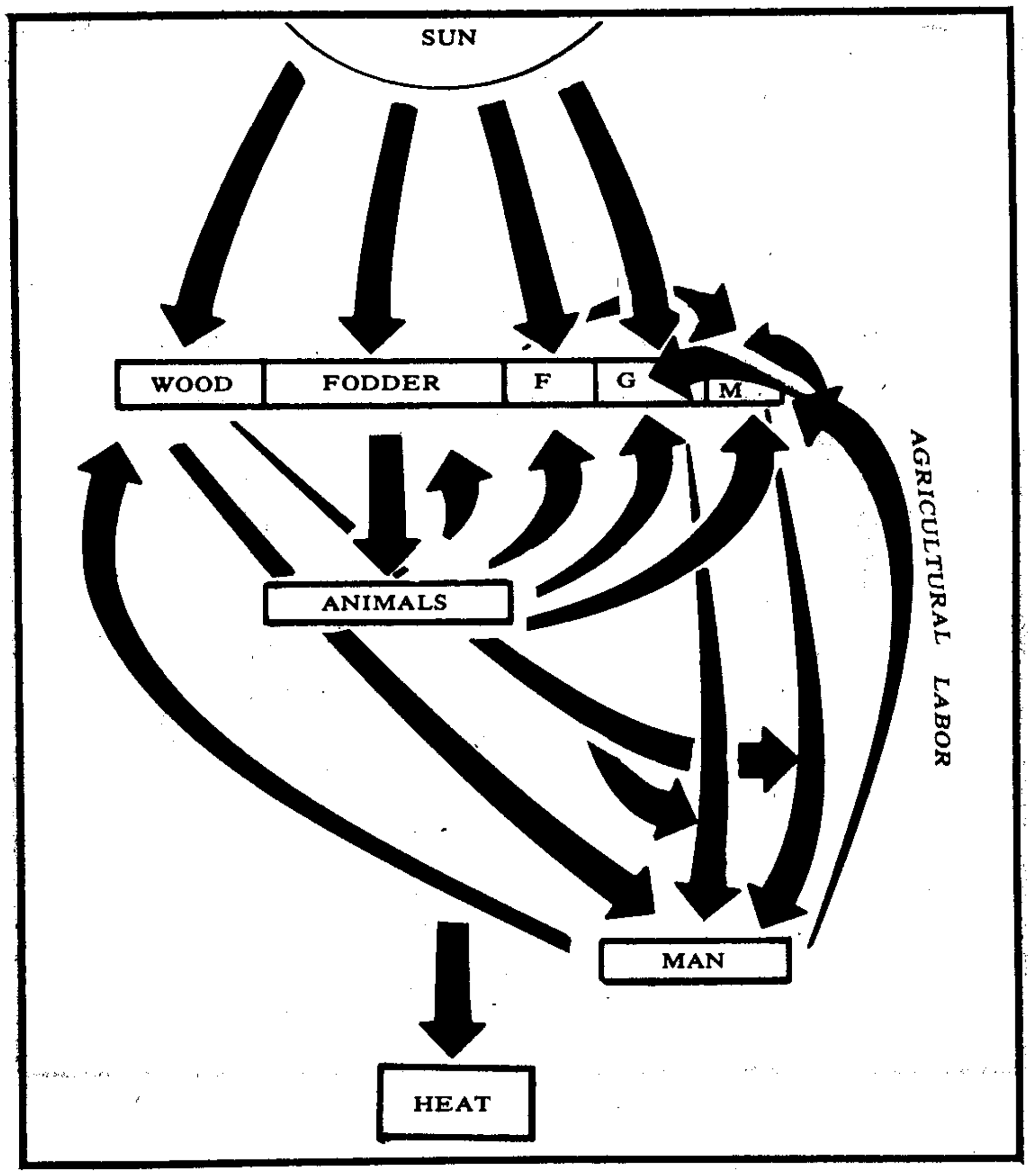


Figure 2c

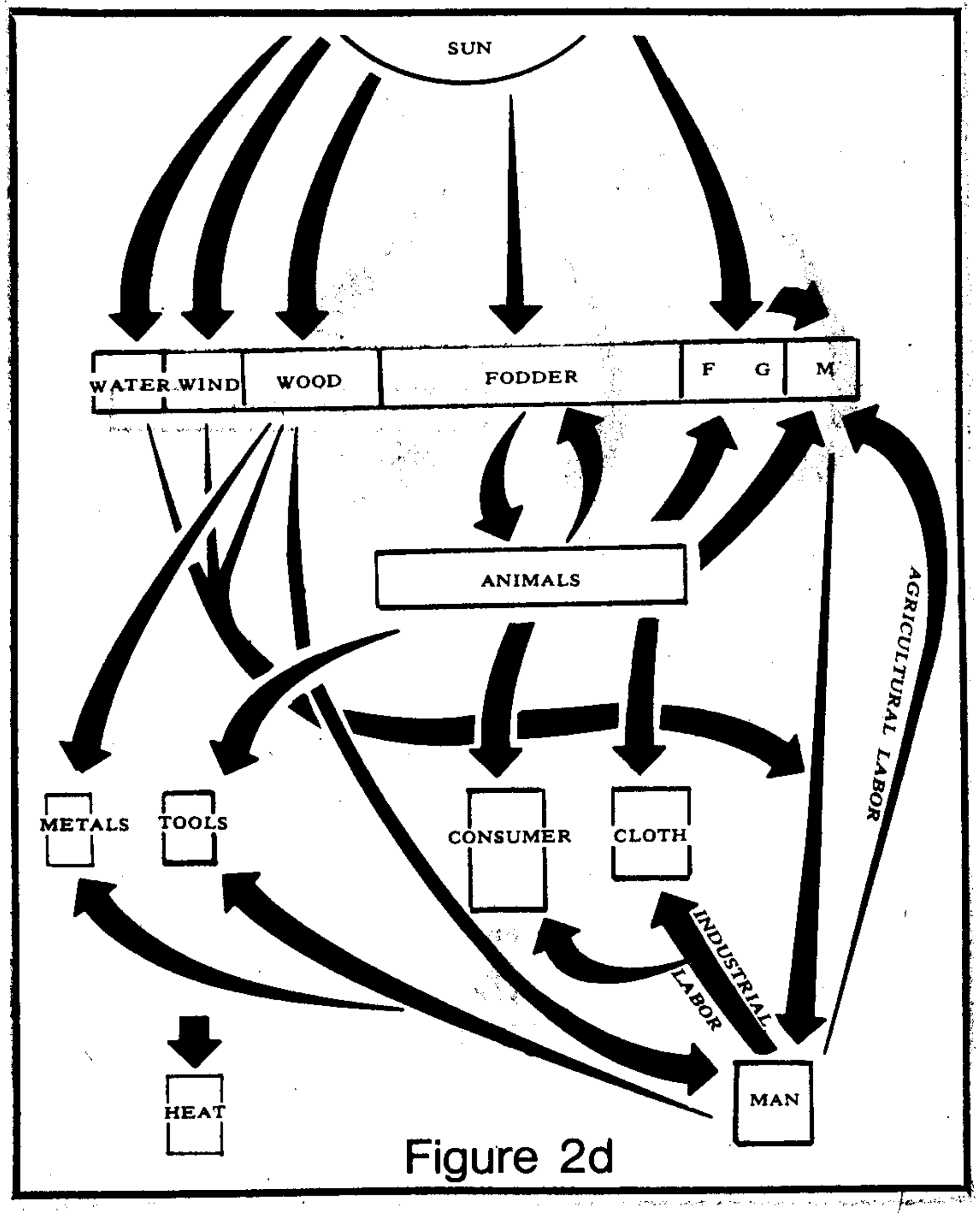


Figure 2d

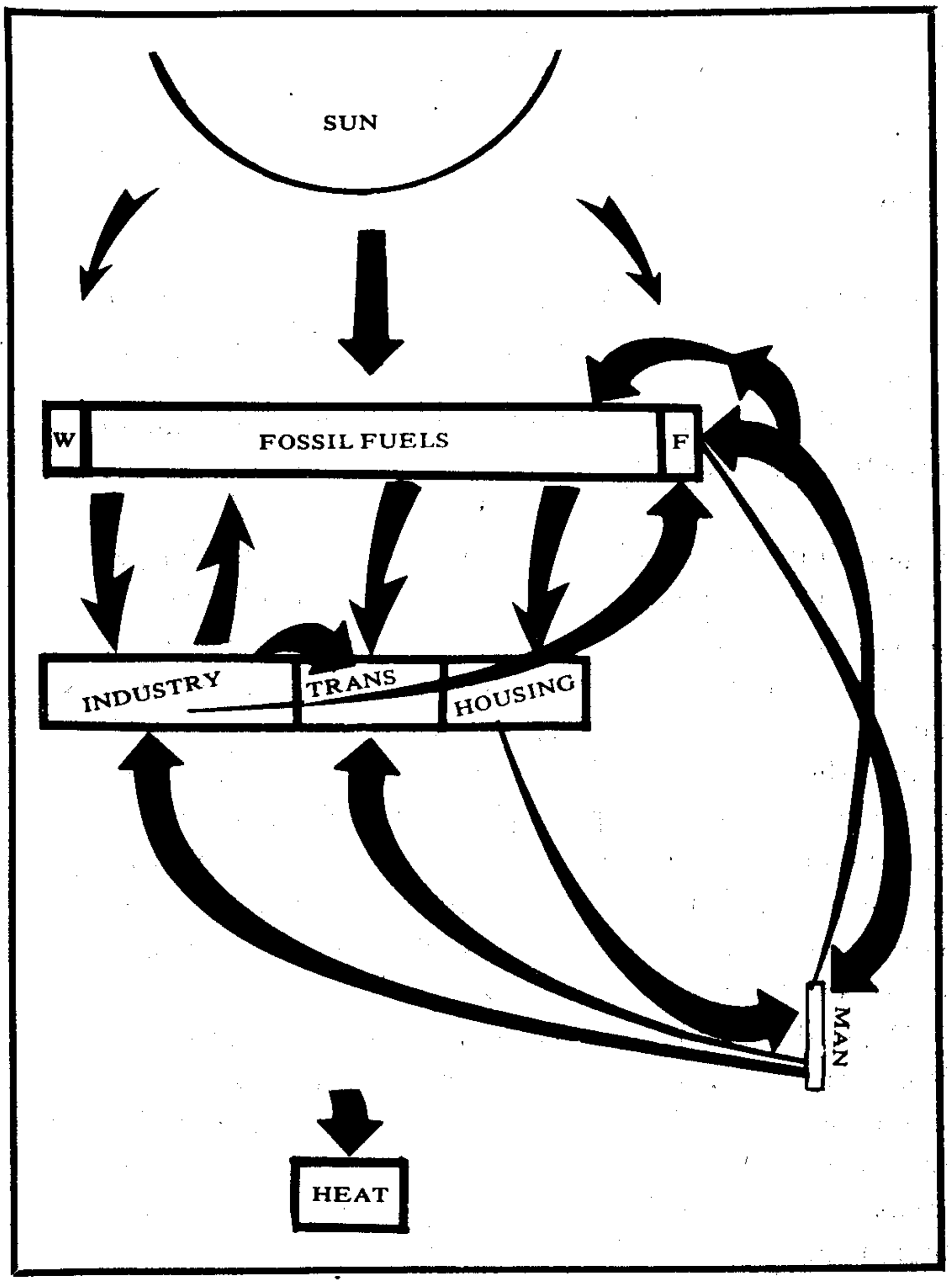


Figure 2e

**F–Feed for Meat and Milk producing animals**
**G–Grain**
**M–Meat and Milk**

Flow of Energy in various stages of Human Social Evolution (schematic). As explained in text, arrows show energy flows involved in human reproduction. Length of bars indicates amount of energy flow. In simplest case, 2a, food provides energy to man who uses it to gather food. At a more advanced stage wood energy, through fire is used to cook meat and other food. At a still later point (2c) animal energy is used to improve agricultural production. (See text for further explanation.)

This rate of surplus itself increases almost without exception, the only reversal being the relatively slow period of growth of early Babylonian and Egyptian society following the rapid expansion of the agricultural and urban revolutions.

The third column shows the exponential rate of increase of the rate of population growth, or the rate of increase (first differential) of the rate of surplus. Again, this rate too increases, and at an accelerating pace. The only exceptions are in the most recent period, and in the above-mentioned caste society.

Thus the general characteristic of social evolution can be expressed in terms of the increase of the rate of increase of the rate of surplus, or a positive value for the second differential of the rate of surplus. Similarly, we can obviously see that the exact same tendency applies to total energy throughput, which is simply the product of per capita flows and total population.

Naturally, this simplified description must be qualified. It represents an overall trend, not the histories of each and every society. Any individual mode tends to reach a dead end, such as that of Chinese society or the situation of capitalist society today. The tables themselves clearly demonstrate the relatively slow evolution of the early civilizations compared with the more rapid evolution of the preceeding neolithic and urban revolutions.

Yet in general each succeeding mode represents a higher rate of evolution on average than the preceding one.

Society thus exhibits absolutely no tendency towards the increase of entropy. Social evolution at any given instant cannot even be characterized in terms of a steady state — a constant distance from equilibrium, such as would be represented by constant population and energy flows. A given instant of social development must be characterized by a rate of motion away from equilibrium, a rate of production of negentropy — an exponential increase in population and per capita energy flows. Each separate mode of social evolution of reproduction can similarly be characterized by a relatively constant *increase* in the production of negentropy or an *acceleration* in motion away from equilibrium. Each mode represents, therefore, a relatively constant rate of negentropic *evolution*. Social development as a whole, finally, must be characterized by an *acceleration* in the production of negentropy, or an increase in the rate of negentropic evolution.

This negentropic characteristic of evolution is not limited to the period of the past million years, but applied to universal history generally, in both the organic *and inorganic* realms. This can best be illustrated by a brief consideration of the inorganic evolution which lead to the formation of life, as it has been outlined by Oparin and others.

The first phase of this process was the production of large quantities of amino acids and other relatively complex high-energy molecules from the primitive inorganic constituents of the earth's atmosphere, ammonia, water and methane. Such initial production of primary organic molecules led to consequent creation of a primeval biochemical "soup," a step away from equilibrium conditions. Chemical calculations have demonstrated that the equilibrium concentration of organic molecules, especially amino acids, would be quite negligible in the conditions existing on earth some four billion years ago. Yet experiments with electric discharges and shock waves have shown that the production of organic molecules in conditions of non-equilibrium energy fluxes is extremely high. In certain cases, for example, nearly half of all ammonia present was converted to amino acids by the passage of a single shock wave.

The next phase represented an acceleration of the motion away from equilibrium. On the one hand, the amino acids tended to polymerize into polypeptides, the forerunners of proteins, which were capable of undergoing far more rapid rates of reactions than the monomers which formed them. Secondly, and even more significant, the polymers tended to clump together into small droplets of concentrated material called coercervates. These coercervates in turn tended to further selectively concentrate certain chemicals within themselves, further removing the ocean from a state of equilibrium mixtures and vastly accelerating the rate of reactions as concentrations of reactants increased.

The gradual development of more complex systems of reactions, including the catalysis of the formation of certain polypeptides by others, led to a further acceleration of chemical evolution and a further increase of energy throughput-rates. When this process culminated in the origin of the first actually reproductive organisms, these primitive catalysts had developed into highly active enzymes capable of accelerating reaction speeds by upwards of one million times through very specific metabolic pathways.

The early development of primitive life shows a continuation of this negentropic trend of inorganic evolution. The evidence of presently existing life shows that a definite sequence of metabolic processes evolved. The earliest processes were based on the metabolism of existing organic molecules whose energy content was ultimately derived from the initial process of formation. These fermentation processes went on in the absence of free oxygen. With the development of more sophisticated chemical coordination, greater energy flows were made possible.

Oparin outlines the following sequence of fermentation modes of metabolism.

Butyric acid fermentation

$C_6H_{12}O_6$ (sugar) $\rightarrow CH_3CH_2CH_2COOH + 2CO_2 + 2H_2$ + 15 calories

Lactic acid fermentation

$C_6H_{12}O_6 \rightarrow 2CH_3CHOHCOOOH$ + 18 calories

Alcohol fermentation

$C_6H_{12}O_6 \rightarrow 2CH_3CH_2OH + CO_2$ + 28 calories

Again we note the *accelerating* increase in energy flow per unit mass.

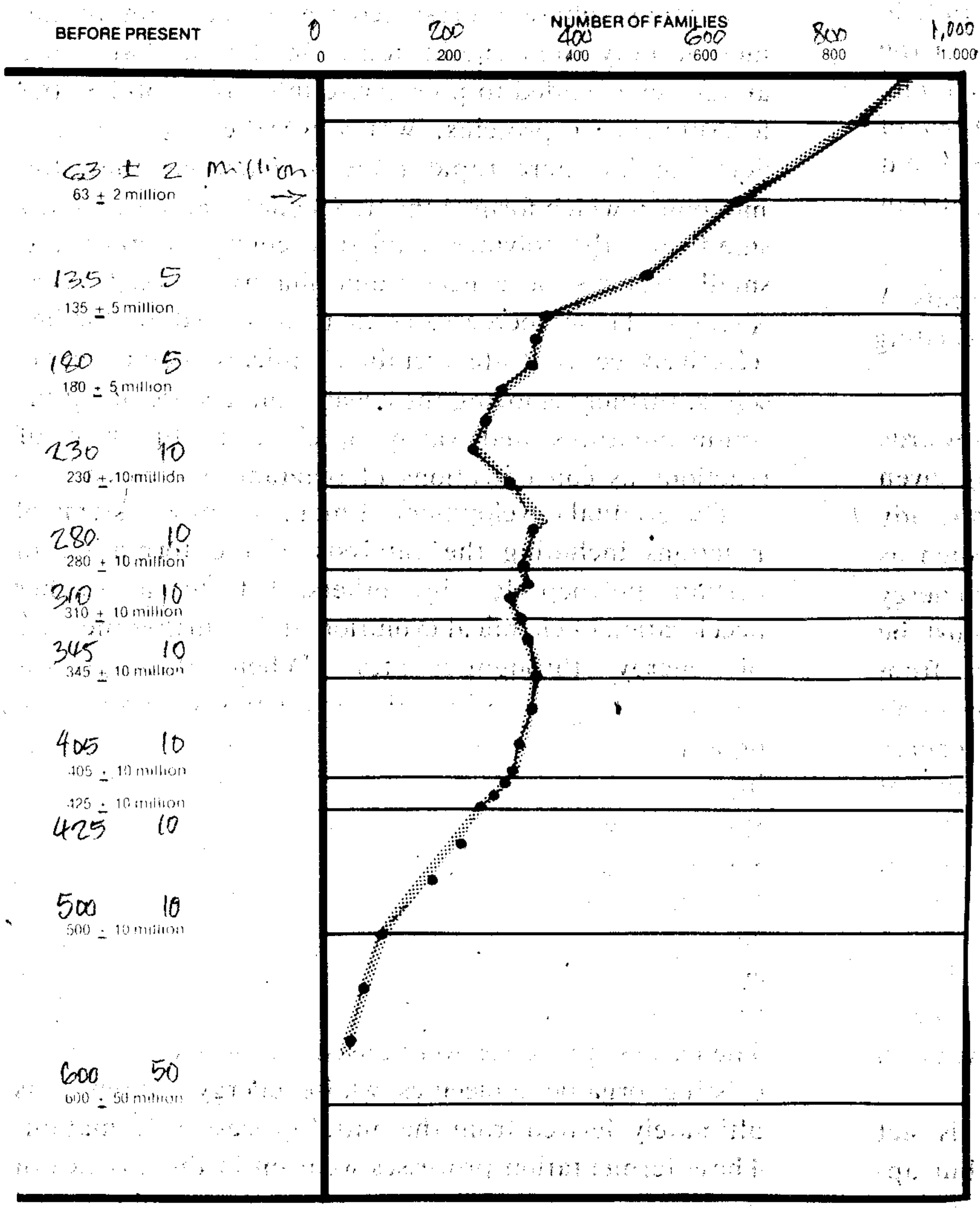
Finally, with the initiation of photosynthesis, large-scale energy directly from the sun is made available. The breaking down of $CO_2$, made possible by photosynthetic utilization of solar energy, releases free oxygen into the atmosphere and makes possible vastly increased energy flows through respiration:

At the same time as this per capita energy flow is increasing, the process of photosynthesis enormously enlarges the total energy flows available and leads to a rapid and enormous increase in the total "population" or biomass present in the biosphere.

Thus we have again the same tendency as shown in the case of human development for the increase in the free energy ratio and the acceleration of this rate of increase.

It should be no surprise at this point that the process of biological evolution itself shows precisely the same negentropic tendency. The marked increase in per unit mass rates of flow is sufficiently obvious by comparing metabolic rates of primitive invertebrates, fish, reptiles and finally mammals. Similarly, the paleontological record gives more than adequate evidence of the general acceleration of rates of evolution, and of the implied acceleration in increase in the total biomass. See Figure 3.

The general point is clear. The entire history of development is in absolute contradiction to what is



The expanding curve at the right indicates how the number of major families of fossil animals increased through geologic time. The sharp decline around 230 million years ago reflects the most dramatic of several mass extinctions.

Figure 3

expected by reductionism. Instead of a slow decline towards equilibrium, there is an ever-accelerating evolution away from equilibrium, a decrease in the time scale of evolution from the billions of years of pre-biological evolution to the decades of capitalist social evolution and the still shorter time scale of the present revolutionary period. The entire process can be crudely summed up in a last empirical comparison.

If we take the rate of energy flow per unit mass as a measure of negentropy, we can directly compare inorganic, organic, and social evolution in an heuristic manner. We take the conditions in the thermonuclear core of the sun as representative of inorganic evolution, the metabolism in a human being for biological processes, and the rate of energy flow in a thermonuclear reactor as characteristic of socialism.

The basic trend of evolution is then expressed by the relative magnitudes of these figures: 1 for the solar core, 10 for human metabolism and ten trillion for the fusion reactor.

## III. Darwinian Evolution and Its Refutation

The reductionist method of explaining the negentropic process of development we have described and overcoming the blatant contradiction with entropic thermodynamics is that of Darwinian evolution. Darwinism attempts to interpret evolution as the result of competition between relatively independent reproductive sub-systems. In this competition, the individuals with the highest reproductive rates, that is those with the highest number of offspring which survive to reproduce in turn, become dominant. As this competition continues, the theory goes, there will be a tendency towards higher and higher net rates of reproduction and thus a tendency for increased rates of negentropic growth for the ecosphere as a whole. Eigen has attempted to apply the same conception to the question of pre-biological evolution, substituting the coded proto-nucleic acid or polynucleotide for the individual plant or animal in biological Darwinism.

Any more than superficial examination of the thermodynamics of the Darwinism model — natural selection based on random mutations — leads immediately back to fundamental contradictions. First of all, the concept of differential reproduction can not explain the origin of reproductive systems themselves. Postulating reproductive polynucleotides in effect merely pushes the problem of the origin of life back one step — where did such polynucleotides come from? The only answer in the Darwinian system is "chance mutation" of non-reproductive systems. Yet studies have shown that such "chance" creation of reproduction is statistically so unlikely as to constitute a miracle.

More important, Darwinism can explain negentropic processes only as a short term aberration, since it leaves the conception of finite resources, finite potential energy,, unchanged. The competition of various individuals and species goes on within the context (environment) of a continually dwindling supply of total resources — monomers in the case of pre-biological evolution, available energy supplies for biological evolution, large game for hunting societies, agricultural land and fossil fuels for civilizations. In this situation, there is no necessary correspondence between the reproduction of individual species and the continued development of the ecosphere as a whole. Quite the contrary.

The most successful species reproductively would be those that in fact compete most successfully for the dwindling resources and thus deplete them the most rapidly, leading to the most rapid contraction of the ecosphere as a whole, while the most ecologically beneficial species would be those which were the most "altruistic" and consumed the least energy and other resources. However, in a context of dwindling supplies, these species could not be expected to survive. By social analogy, the ecologically sound human beings in a world of fixed resources are those "altruistic" workers who reduce their caloric consumption to 1000 calories a day in order to preserve the environment, while those who would survive are the ones who can take the most from the rest of humanity. Thus we have the famous formulation of Darwinian evolution — the Survival of the Fascists.

We arrive back at the original contradiction — an ecology which is negentropic cannot survive and one that survives must eventually reduce its energy flows and reach equilibrium or at least a steady state. If we take an isolated system — a part of the ecosphere — we do indeed find just this "ecologically" sound tendency towards reduction of energy flows. The development of a climax forest from a bare plain, for example, involves the succession of species of continually lower energy per biomass throughput. But we have seen conclusively that such a description cannot be applied to the ecosphere as a whole.

The problem is that the actual evolution of the ecosphere has involved a continual re-definition of what constitutes resources and available energy. Each individual mode of reproduction does indeed appear to be exhausting finite resources. Yet a new mode always appears which opens up the exploitation of *new resources*. Thus we have the initiation of photosynthesis, the *direct* consumption of solar energy, at the point at which fermentation processes would have exhausted available energy supplies in the primeval "soup." Similarly, in social evolution, each change of mode illustrated in Figure 2 involves a new resource, an enlargement in the amount of energy available. Wood supplements food, agriculture allows the much greater and more direct exploitation of photosynthetic processes, fossil fuels replace wood, and fusion power replaces fossil fuels. New needs are also produced, and thus again new resources — such as the need for metals in civilized communities, and the new resource of ores. What is defined as an "ore" equally obviously depends on the level of mining and refining technology available.

The negentropic evolution of the ecosphere is made possible only through this succession of qualitatively different modes of reproduction, the overcoming of apparent "ecological crises." Therefore, the evolution of individual species cannot be explained in terms of their own independent development, but only to the extent that they enable the ecosphere as a whole to qualitatively evolve, to use an expanding total amount of energy flows. Thus at the first "fermentation crisis," the species which evolved were not those which could ferment the fastest, but photosynthetic plants which could open up, through the production of free oxygen and the simultaneous development of respiration, new energy sources for the entire ecology. The fact that photosynthesis could only develop in conjunction with respiration (since otherwise supplies of carbon dioxide would be rapidly depleted) itself shows that the evolution of individual species can only be comprehended from the standpoint of the evolution of the ecology as a whole.

We can summarize the basic problem. Since reductionism defines the universe in terms of discrete entities, by this very definition it posits a hard and fast division between such entities and their unchanging "environment." The axiom of discreteness actually necessarily implies the "axiom" of fixed relationships or fixed enviroment. But the real ecosphere is not isolatable from some separate enviroment, and in fact continually modifies such an "enviroment" in modifying its mode of reproduction, its relationship to the rest of the universe.

This problem leads to a related one.

Reductionism assumes that relationships can be defined in isolation from the actual ongoing process of evolution. In this way reductionism makes human reproduction into a purely consumptive process — energy and resources being derived from the environment and the productive process terminating in the production of products on the one hand and waste (heat and pollution) on the other. The point is illustrated by the diagrams of Figure 2, in which the energy flows terminate in industrial production. Following precisely this reductionist line of reasoning the Physiocrats concluded that only agricultural labor, that is those energy flows which directly contribute to human consumption of energy (food), is productive, and industry is essentially parasitic. The actual continual decrease in relative importance of agriculture and immediate human food consumption as illustrated in Figure 2 totally refutes this notion. The development of industry, the production of tractors and fertilizer, has in fact led to the enormous increase in agricultural productivity and the concommitant decrease in total agricultural labor.

Thus Darwinism and the reductionist axioms on which all existing bourgeois science is based are conclusively refuted by the evidence of the last two billion years of evolution. Evolutionary development is inexplicable from the standpoint of fixed resources relationships (such as self-evident particles, etc.), independent of reproductive relations. And the continued capability of evolution to proceed to ever higher states of negentropy through the creation of new resource relations is equally inexplicable except as a series of chance, highly improbable events. From the reductionist standpoint, evolution remains a series of miracles in a world of entropic processes. On these grounds reductionism must be decisively rejected.

## IV. The Actual Basis for Human Reproduction

We must then answer the question — how is human reproduction possible? How does negentropy continue to increase? In other words, how can we view the energy and the universe in such a way which makes the process of expanded reproduction coherent? And, how can we plan and control this process?

We begin from the actual existence of man, and his actual evolution, the empirical evidence of negentropic development. This poses the problem of developing a conception of the universe based on continuity, rather than discrete entities, and on self-development rather than fixed relations — a self-perfecting continuum.

To develop this conception, we proceed to an analysis of human reproduction, approaching it from the standpoint of the process as a whole, from the standpoint of socialist planning. Using this standpoint, we simplify the problem by considering an economy without waste or unemployment.

We begin by asking what the preconditions are for the reproduction of the population as a whole? Clearly the conditions of reproduction of any single individual cannot be considered for the individual alone. Each individual's existence depends not merely on the biological reproduction of his or her parents, but on obtaining the necessary food, clothing, housing, etc., needed to maintain life. These goods are produced by a complex network of individuals extending over the entire globe, who in turn are dependent on each other for continued existence.

Thus, the development of the population as a whole depends self-reflexively on the development of the population as a whole. That is, the population is

Figure 4

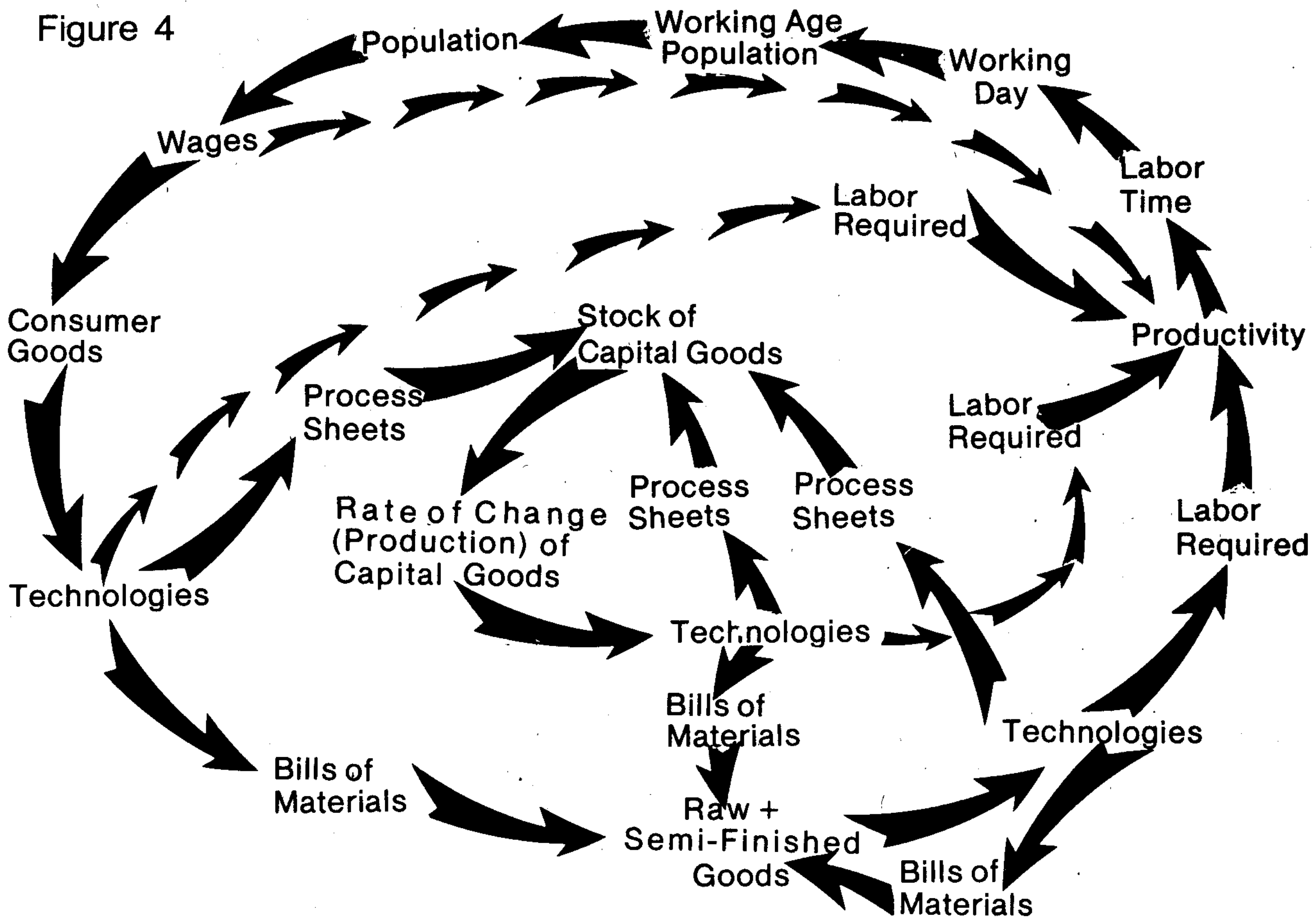


Figure 4 shows the self-determination of the population through the process of production. To take the example of food production, the population, together with the per capita food requirements, determine the amount of food produced. The technological mix of, say, mechanized agriculture and the bills of materials determine how much raw materials, such as fertilizer and fuel, is required. The process sheets determine how many tractors are required, while the change in the number of tractors (rate of production) in turn determines, through further choices of technology and process sheets, the number of machine tools which must be on hand, the amount of steel which must be produced, etc. Finally, the labor requirements determine how many agricultural workers, chemical workers, steel workers, machinists and so on are required.

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determined as that population which is necessary to produce the preconditions for the existence of the population.

To find these preconditions we begin by describing the total population at a given time as a distribution of population density over age, and by productive ability, or level of skill, which in turn depends on such things as past education, standard of living, etc. To maintain this productive level, each individual needs a certain consumption of various goods, or *wage rate.* The population, together with the wage rates for each age and skill group, determines the total output of *consumption goods.* The production of a given quantity of each type of consumption good requires a determined amount of various raw and semi-finished materials. This *bill of materials* in turn is determined by the various *processes* or *technologies* which are employed in the production of each good at a given point in time.

From the total production of consumption goods, the technologies or mix of technologies employed and the bills of materials, we can determine the portion of *raw and semi-finished production* devoted to producing consumer goods.

From the technologies and the *process sheets* which state what capital goods are required for production of a given good, we can determine the total *stock* of capital goods for the rate of production of goods previously determined. From the rate of change of this stock, we can determine the total *production of capital goods* and from further bills of materials, the total amount of raw materials necessary to produce this amount of capital goods.

Finally, from the *labor requirements* of each good and the *productivity of labor* (itself dependent on the wage rates), we can determine the total *labor time* required to be supplied by labor of various skill levels for the total production demanded. From the *length of the working day* and the labor time, we can determine the total working population required.

If we include the similar calculations necessary to determine the size of the work force engaged in essential services, such as transportation, education, etc., we can obtain the *total work force*, which, from the standpoint of socialism is identical with the *total working-age population.*

These interrelationships are summarized in Figure 4, and are expressed mathematically in the appendix.

If we examine the development of this reproductive system over a period of time, we can see that the growth of human population is not an "independent variable" based on the number of births and deaths, but instead the population, births and deaths are all determined by the general evolution of the economy, and in particular by the development of technology. Specifically, if we know the development over time of the wage rates and the technologies employed, we can strictly determine the evolution of the working age population, the stock of capital goods, and the production of all goods. Further, it is clear that once the development over time of the working-age population is known, the development over time of the entire population, including those below and above the working age, must be determined.

Finally, since we must begin from a given point in history at which time the size and distribution of the population and stock of capital goods are determined for us by previous development, we find that by including these "boundary" conditions, we can determine from the development of the technologies employed *alone* the development of the wage rates and everything else.

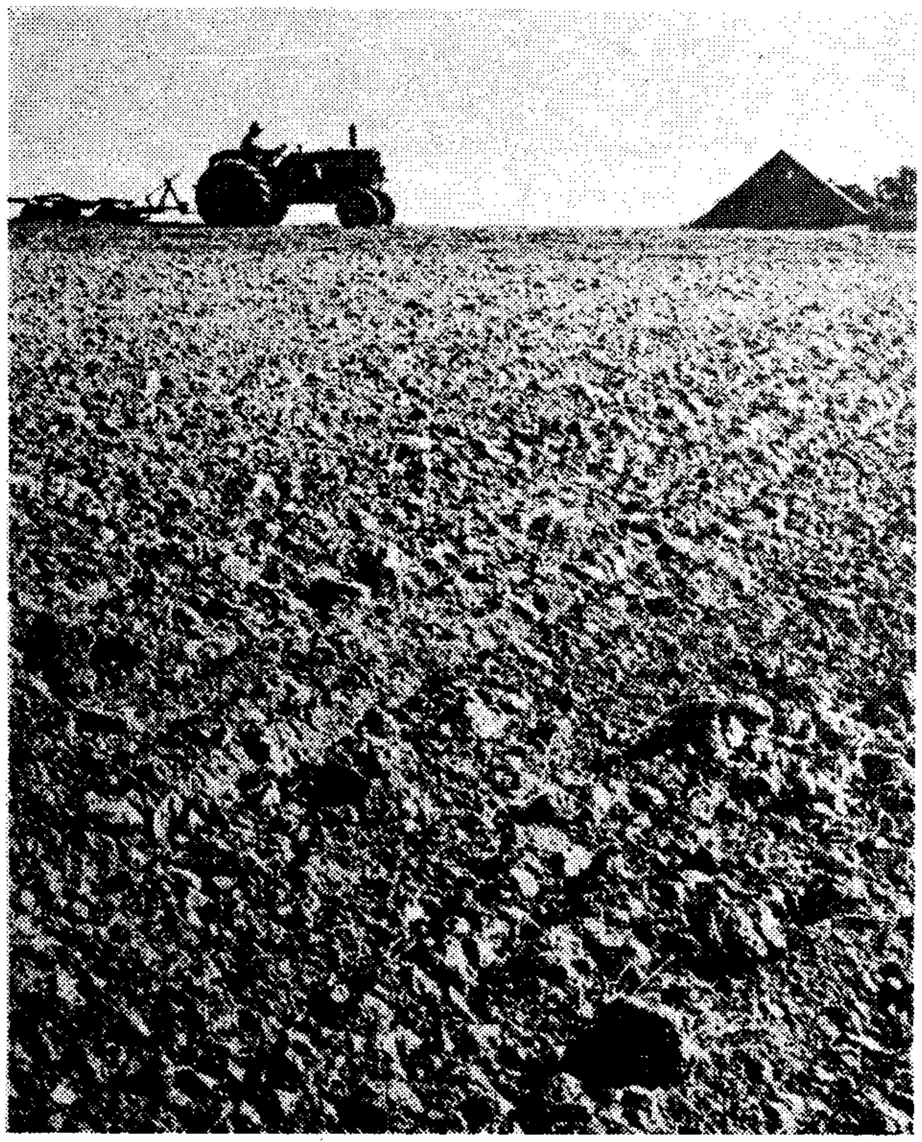
The relationship of the evolving human economy to the ecosphere as a whole is expressed by changes in the bills of materials and other coefficients with time. As resources are exhausted relative to any given technology, the amount of energy, capital goods and labor involved in obtaining them increases, and this increase is itself strictly determined by the existing state of the ecosphere and the past history of development of human society.

From this description of the development of human population and productive relations, we can draw certain preliminary conclusions. If we visualize the development of the population as a path of "world-line" through time, then this path is totally defined by the path of development of technology. If we consider all conceivable paths of development of technology (such as implementing fusion power in five, six or seven years, in mechanizing all of agriculture in seven years, or only 50 per cent, applying one or another type of automation, etc.), we find that only some are actually possible, insofar as for many such paths *no* possible development of the population will maintain the *invariant* relations of production which we have defined. For example, some plan to introduce fusion technology in an arbitrarily short time would require the existence of a large, highly-skilled work force which could not be produced in such similar short time, and thus no possible path of development of the population would correspond to this plan.

Thus we have, for any mode of development, a *surface* of all possible paths of development of populations and technology. Each path, and thus the *Riemannian* surface as a whole, is defined as *invariant*, in the sense that the population-path is that path necessary to reproduce itself under the given conditions of technology.

Certain characteristics of these surfaces of population development are also clear. Since any reflectively fixed mode of production would lead to a continual shift upwards of the cost of raw materials as those were exhausted, any such mode, and the surface corresponding to such development, must eventually end. That is, a point is reached where the invariant conditions can no longer be maintained and the mode collapses. Any continuing mode, or series of modes must be characterized by a continual upwards shift in technologies, accompanied by a continual upwards shift in the skill levels required — and thus in consumption levels — leading to a more rapid depletion of relative resources and thus a more rapid shift of technologies.

For example, in the present situation the continuation of fossil fuel-based technologies for another few decades would lead to such depletion of the productive apparatus and population that a collapse would be unavoidable. A shift to the next mode or surface, on the basis of fusion power, is thus imperative before that time.



Thus, viewed from the standpoint of a coherent self-reproductive process, the tendency towards the acceleration in the rate of increase in per capita consumption levels and therefore in per capita energy consumption, that is, the negentropic tendency and the accompanying changes in reproductive relations, becomes a clear necessity of continued development.

But the general question of human population remains unresolved. What we have done is given a *formal* description or model of human reproduction. Two questions remain unanswered. First, we have defined the range within which the actual development of the population must lie, but not what that development is. We have not, from the standpoint of planning an economy, defined what the optimal plan is or the criterion of optimality. Secondly, we have not accounted for how new technologies come into existence, which is the central problem. We have merely assumed that such new technologies are available. These technologies are defined outside the boundaries of our formal description.

To go beyond this point we must return to empirical examination of the process by which man actually reproduces himself. The crucial aspect which cannot be represented in the formal model is the actual creative mentation which lead to the initiation of new technologies. As Koehler's experiments with apes demonstrate, discovery — even among animals — does not occur on a chance basis. Certain preconditions are necessary and simultaneously virtually assure that new reproductive relations will be established.

Koehler's experiments consisted in essence of posing a problem for the apes which could not be solved by methods to which they were accustomed, but only by creating new tools out of a variety of materials provided. For example, in one famous case, a banana is suspended from the ceiling out of reach of the chimp, and a box and a stick are among the objects in the room. The chimp created two new tools by moving the box under the banana, standing on it, and knocking the fruit down with the stick.

The actual results of these series of experiments illustrated in simplified form the two necessary preconditions for creative mentation. First, a problem requiring creative solutions must be at hand. Second, a minimum level of variety of existent objects and relations must be available from which the new relation can be formed.

Human reproduction creates for itself both of these preconditions. By exhausting the resources relative to any given set of reproductive relations, or mode of reproduction, man poses for himself problems requiring creative solutions. At the same time, man's previous activity in modifying nature and creating new relationships, provides him at every moment with an increasingly rich *variety of existing relations* from which new modes can be created. Thus the very process of producing new relationships, new modes of reproduction or technologies, *recreates the preconditions for further production of new relations.*

This self-reflexive process of creating new productive relations is the basis for human negentropic evolution. Since the very production of such relations increases the rate that new relations are formed (relations among relations), the rate of production of such relations, the rate of differentiation, must itself continually increase, and increase at an accelerating rate. Thus we have man advancing from using a small number of primitive tools to a larger number of types of tools made by the primitive originals, to a still larger number of types made with these secondary tools, and so on. Similarly, the free energy ratio, the ratio between the number of existing relations and the rate of formation of new relations, must also increase — thus producing the observed tendency for the increase of thermodynamic negentropy. This increase in the rate of differentiation is in fact the increase in the actual capacity of the economy to evolve and thus to further increase this rate, or *dialectical negentropy.*

The absolutely necessary accelerating increase in the size of population is also comprehensible from the same standpoint. The increase in the number of people leads directly to the increase in the richness and variety of relations among the population, the quantity of relations that any individual has, and therefore is absolutely necessary to increase the creative abilities of the population and the rate of change of the relations of production. These changes in the relations of production in turn both allow, through greater production, and necessitate a further increase in the rate of growth of the population. The quality of the population is thus directly linked to its quantity.

This quality, labor power, can thus be defined as the capacity to produce new relations, to increase dialectical negentropy.

We can now resolve as well the second of our unanswered questions — what is the optimum path of human reproduction, the general criterion for socialist planning and program? This optimum can only be defined as the path which maximizes at every point in time the rate of differentiation and thus the capacity for further evolution. Any particular mode of development is characterized by the expansion of those parameters which at the time most critically limit the production of new relations. The path that involves the most rapid removal of these restrictions, and thus the most rapid passing to the next mode, is that defined as the "geodesic" path for that mode. The overall invariant tendency which connects the various modes of development is the continuous increase in the rate of differentiation — the succession of modes is defined by this overall invariance.

In the present economy, for example, the principle restrictions on the capacity of humanity to create new productive relations is the severe constriction of consumption goods available to the bulk of the population. A variety of such consumption goods are essential to give each individual command over sufficient material relations so as to enable them to create new conceptions, conceptions needed for any sort of skilled labor. Without a much higher level of consumption, labor power will be aborted.

Thus the basic criterion for development in the period immediately ahead must be the most rapid possible rise in the level of consumption. But this in turn implies the absorption of energy and raw materials on a greatly expanded scale, such that the limited availability of fossil fuels and ores would very rapidly become the principle restriction on increases in standard of living, and thus on development as a whole.

Therefore, the general mode of reproduction of the immediate coming period must be principally characterized by the most rapid implementation of *fusion power.* Through the adoption of a fusion-based economy, all energy needs for the next several decades can be met. At the same time, fusion torch processing of ordinary rock can eliminate all shortages of raw materials.

The development of an advanced fusion-based economy in turn prepares the way for the next general phase of development, in which the main limitations on human creativity will come from the length of the working day and the technological goals will be defined in terms of the maximum automation of labor.

The standpoint we have outlined of dialectical negentropy allows us to deal with the problem of the relation of the evolving human society to the ecosphere as a whole. The process by which human society utilizes nature is the transformation of existing relations in nature into reproductive relations for society. It is the creation of new relations in the ecosphere as a whole — the differentiation of matter. Thus the separation of pure copper from ore is characterized by the creation of new relations in nature into reproductive relations for society.

Thus the separation of pure copper from ore is characterized by the creation of new relations, such as the use of copper as conductors, or in tools, etc., which in no way exist in the undifferentiated ore. The "exhaustion" of resources is simply the reductionist way of viewing the transformation of a whole set of existing relations in nature into relations for society. It is, as we have said, absolutely no coincidence that at this point new technologies — the relations of relations — come into existence.

Thus the increase in the rate of negentropic development of human society is reflected directly in the increase in the rate of differentiation in the ecosphere as a whole, which is symptomized by the increase in the rate of throughput of (reductionist) energy.

Thus, the development of a fusion-based economy, by creating an immensely higher rate of development of the economy as a whole, vastly increases the rate of negentropic flows, as well as the rate of energy throughput as measured by reductionist standards — (measured as if energy consisted of elementary quanta). By contrast, the capitalist schemes for large-scale development of "energy pyramids" like that of the Rocky Mountains, based on coal gasification and other labor-intensive and obsolete methods, only increases the reductionist flow of energy slightly, while rapidly decreasing the actual negentropic energy flows — rapidly depleting the human and environmental potential for further development.

Human development is therefore comprehensible and controllable from the standpoint of dialectical negentropy. The increase of population and consumption leads not to the exhaustion of the ecosphere and the society, but to the more rapid development of new invariant conditions, new relations of reproduction which make possible and necessary the further increase of population and consumption.

## V. Negentropic Evolution of the Universe

The conception of dialectical negentropy which we have applied to the realm of human evolution is also directly applicable to resolving the reductionist paradoxes in the physical sciences. A coherent view of the universe demands from an epistemological standpoint alone that the evolution of the universe as a whole must be governed by the same negentropic tendency as evidenced in the evolution of the biosphere and human society on earth. Rather than devolving from a metaphysical "Big Bang," the universe must have evolved through a series of modes of development, each being characterized by a complexity of relationships and therefore a rate of differentiation greater than the preceding mode, and thus a higher rate of evolution. The rate of development of the universe must have accelerated continuously from asymptotically low values in the infinite past.

Rather than being viewed as a collection of elementary particles governed by fixed laws, the universe must be considered as a succession of continuous Riemannian manifolds of reproductive relations. Physical laws are the changing, historically specific descriptions of the invariant relations of any given mode. These modes succeed each other as the manifolds of relations undergo a process of accelerating self-differentiation, producing relations of relations, and corresponding new invariances.

The reductionist notion of energy as elementary quanta must be replaced by the dialectical notion of energy as flows of negentropy — the production of new reproductive relations. Only such a notion of energy as self-differentiating can be coherent with the known evolution of the universe.

In terms of the mathematical tools available to us to deal with such conceptions, we can term the universe thus described as a Riemannian-Cantorian continuum, a self-differentiating, self-relating space, in which the underlying invariance is the maximization of the rate of differentiation.*

This conception of universal evolution is the only correct starting point for the development of a unified field theory. The actual content of such a theory, which must be able to describe the historical emergence of one set of physical laws from earlier forms, cannot possible be studied in relation to arbitrarily isolated physical systems (such as is done with accelerators, etc.), but only through examining entire "economies" of developing physical processes, such as large-scale astrophysical phenomena.

It is clear that the exact same methodology must be applied to the study of the other main phases of universal evolution — chemical evolution leading to the origin of life and biological evolution. The fact that individual chemical species do not "reproduce themselves" directly is no more reason for not treating the pre-biological "soup" as a reproductive system than the fact that machine tools, steel, houses, etc., do not reproduce themselves is a reason for denying social reproduction. Again, the only methodologically correct approach to chemical evolution is from the standpoint of a chemical "economy," a manifold of chemical interactions, forming as a whole a reproductive network. The concentration of any individual species is determined by the contribution of that species to increasing the rate of differentiation of the chemical economy as a whole (the rate of throughput of dialectical energy or negentropy). Preliminary work on this approach is already underway, and should lay the basis for a fundamental reconstituting of chemistry on a non-equilibrium basis.

Absolutely similar considerations must apply in the realms of biological evolution. Not chance mutations, but the necessity and possibility for the creation of specific sorts of reproductive relations with the entire ecology determined the origin and replication of species. Pre-human ecological evolution selected out those species which maximally contributed to the rate of evolution of the whole, just as today, human selection and breeding, not the individual reproductive potential of plants or animals has determined the course of continuing biological evolution (plant and animal domestication, etc.).

Finally, from what has already been said, it can be seen that human consciousness must itself be a coherent expression of this general process of negentropic evolution, self-differentiation of space. Consciousness can be nothing else than the continuous production of new relations — negentropy production. The distinction between human consciousness and the preceding phases of evolution is that prior to human existence the rate of development of new relations of reproduction was negligible relative to the timespan of the reproductive processes themselves. During the lifespan of a single animal, biological evolution can be neglected — within very narrow limits, the mode of activity of the animal is fixed. Humans are characterized by conscious activity in that they can, through the mediation of changed social relations, change their mode of reproduction in a very short period compared with their lifetimes.

By ending the reductionist Zero Growth view of man as an unchanging animal, fixed in his technology, we simultaneously eliminate the reductionist duality of consciousness and matter, locating consciousness as the continuation of the entire process of universal development, the expression of the fundamental laws of the universe.

## VI. How Development Is Aborted

The general negentropic development of the universe is not a "law" imposed from above, but is simply the direct consequence of the coherence of the universe. In a coherent universe it is essentially tautological to state that the overall rate of development has a tendency to be at a maximum, since any localized tendency in a different direction, any mode of development which begins to increase in entropy, will be rapidly succeeded by a more positively developing mode.

Relatively prolonged periods of *entropic* development, such as the present one, are thus what needs explaining, not the general negentropic tendency of the universe. There can be no doubt that at the moment development is indeed being consistently aborted. Capitalism has

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*The key feature of Cantor's work for us is the notion of relations of a continuum —his conception of transfinite numbers. This conception is more thoroughly discussed in a forth coming **Campaigner** article. We can here merely briefly outline what is necessary for comprehension of negentropy.

Cantor demonstrated that the infinite number which represents the number of all integers, 1,2,3,4 . . . is not the only infinite or transfinite number. It is merely the only one which is countable, even in an infinite amount of time — the only one which can be expressed in terms of discreteness. In particular, he demonstrated that the number of all relationships within a transfinite set is itself a higher-order transfinite number. Thus the set of all integers is aleph-1. The set of all relations between integers, of all ordered sequences of integers, is the number of real numbers or aleph-2. This is also the number of points in a continuum. Similiarly the number of simple relations of a continuum to itself (the number of curves in space) is aleph-3, and so on. In this manner a series, and in fact a continuum of higher and higher order relationships of a continuum to itself may be built up without any reference to discreteness.

destroyed the connection between theoretical scientific advance and technological progress by systematically preventing the application of new technologies in industry. Thus, since about the 1920's, the vaults of major corporations have filled up with patents bought to prevent their use, and thus preserve the value of existing obsolete plants. Gold's article in this issue of the *Campaigner* documents fully the most criminal example of this sabotage in the twenty-year-long campaign of the government to torpedo fusion power.

The result of aborting technological advances has been the rapid drying up in turn of the sources of such advances, theoretical and applied science. The stagnation of theoretical physics, for example, since the late twenties is notorious. The more belated halting of advances in applied science was inevitable once the new conceptions of theory on which such advances must be based disappeared. While during the nineteenth and early twentieth centuries fundamental technological advances such as the radio, the airplane and the telegraph came at a rate of several per decade, at the present time no such technological advance has been achieved since the invention of the laser fifteen years ago! For the first time since the beginning of the industrial revolution more than two hundred years ago, more than a decade has passed without major technological innovation.

The destruction of the existing productive potential is equally blatant in the collapse of consumption, the starvation and destruction by disease of tens of millions, the cannibalization of existing means of production, the annihilation of entire industrial sectors.

Capitalism, acutely in the past few years and chronically since the time of World War I, has become a parasitic growth on the entire world economy, entropically exhausting existing resources and destroying, rather than enhancing, humanity's potential for further evolution. It is this cannibalism of humanity and the ecosphere as a whole which constitutes the real ecological crisis facing us today.

How can we reconcile this parasitic destruction with the negentropic tendency of universal development?

Episodes of cannibalistic, entropic development are scarcely unknown in human history — the collapse of feudal Europe in the fourteenth century, of the mercantile system in the sixteenth and seventeenth, of the Roman Empire in the second through sixth centuries. Yet such episodes are completely confined to the past six thousand years — that is, to the period of caste and class society. Nothing analogous can be observed, for example, in the course of biological evolution. While large-scale setbacks in the course of evolution did occur, most notably in the Permian period (see Figure 3), all evidence points to these being the result of shifts in the environment which were simply too rapid to be fully adapted to by the existing mode of evolution, such as the widespread mountain building and contraction of the oceans which led to the contraction of ocean life during the Permian. The phenomenon of entire evolutionary systems becoming parasitic and actually aborting the development of new modes is entirely unique to a single phase of human social development.

Unique though it is, the period of class society and its parasitic tendencies are not inexplicable or anomolous — they are inevitable features of a certain stage of human development. Human social development is distinguished form the preceding biological phases by the universal nature of the human species. That is, man, through his social relations, has the potential to act as a universal species, altering the ecosphere as a whole. Individual humans are species-beings, universal beings, because they have the potentiality to alter the course of evolution as a whole through their interaction with humanity as a whole, through language, culture, etc. Yet since man did evolve out of non-universal species, this universal character of humanity has remained a mere potential until the present. Human society, until several thousand years ago, was in fact broken up into hundreds of thousands of tiny bands, villages and tribes. While cultural intercourse did take place between these tiny fragments, man's actual reproduction was not carried out on a worldwide or in fact any extended scale. It was the historic task of caste and class societies to abolish this fragmentation and to objectively unify humanity into a single economic and cultural whole, to build up the preconditions for actually universal, actually human relations.

The parasitic, cannibalistic aspect of class society evolved out of this process of unification.

From the origin of caste society in ancient Egypt and Mesopotamia, caste and class societies have functioned, through organized looting, to forcibly concentrate wealth on an expanding scale. Each new civilization created a larger unit of social intercourse on the basis of its forcible incorporation of wider circles of humanity into its empire. Thus despite the huge waste and destruction inherent in the class societies, and the road blocks which they put in the way of further evolution, the enormous economic advantages gained by the greater degree of unification ensured the dominance of each succeeding society.

During each expansionary phase, the parasitic side of class domination, of forcible appropriation of wealth, was overshadowed by the real expansion of wealth. Once each society reached its specific limits of expansion, the looting was diverted inwards, bringing on a period of entropic devolution. Since the fetters of existing class rule held back the development of new social modes, these periods of devolution continued until the society was sufficiently weakened to be overturned from within or invaded from without. Thereafter, new and broader empires and societies arose on the basis already formed by their predecessors.

Thus through six thousand years, humanity advanced towards a universal society and a universal division of labor, on which alone the continued growth of population could be based, at the cost of millions of lives lost in wars, famines, and plagues, whole regions converted into deserts, the oppression, enslavement and annihilation of entire populations. By the end of the nineteenth century, capitalism had completed the task, and had formed the entire human population into a single world economy. The progressive role of class society was at an end.

But capitalism and class society with it did not cease to exist. Through wars, depressions and revolutions, capitalism up to this point has managed to maintain the grip of its chains of illusion on the minds of humanity. Having outlived its expansionary phase, capitalist society now uses its control over the productive resources and population of the entire world to destroy them.

At this writing, we can conclusively state that the end of this final death agony of class society is at hand. The only question is how that end will come. In the next few years, and to a large extent the next several months, the issue will be decided — either class society will end with the total cannibalization of the human population, nuclear holocaust and the return of humanity to barbarism, or perhaps final extinction, or humanity will cast aside the fetters of class rule and appropriate for themselves the fruits of historical development — the creation of an actually universal society, the subjection of evolution to the conscious control of a united humanity.

The outcome is not determined by some impersonal laws of the universe, but by the conscious decision of millions of human beings, the decision to free themselves from the bounds of the fixed universe of Zero Growth and to take into their own hands the guidance of history.

It is this alone which will determine the future existence and growth of the human population.

# Appendix
## An Outline of a Mathematical Model of Socialist Reproduction (Productive Sector)

We begin by representing the population as a continuous distribution over age and "skill level" and as a continuous function of time

$$P(a,s,t)$$

where P is population density at age a,skill level s,at time t.

The total production of consumption goods can be derived from this. We define the wage levels as the per capita consumption of a given consumer good

$$W(a,s,g,t)$$

where w is the per capita consumption of good g by people of age a, skill s, at time t.

For durable consumer goods, like housing we have W' similarly representing the stock of durable goods needed.

Total production of non-durables is

$$C(g,t)=WP$$

where C is production of good g at time t. The multiplication involved is that of tensor multiplication or linear projection. That is,the sum of the products of wages and population for each age and skill level yields the total production.

Similarly for durable consumer goods,ignoring for the sake of simplicity depreciation (which we will do throughout), we have production is the rate of change off the stock.

$$C'(g,t)=d/dt\,(W'P)$$

where d/dt is the symbol for rate of change with time.

So total durable and non-durable consumer goods production is

$$\underline{C} = WP\,/+d/dt\,W'P$$

We then determine the proportion of each consumer good which is produced by any particular technology

$$\bar{C}(r,g,t) = T\,(r,g,t)\,\underline{C}$$

where $\bar{C}$ is tht total production of good g at time t by process r, and T is the proportion of good g produced by process r at time t.

We then have the production of raw and semi-finished goods for the production of consumer goods

$$S\,(c,t) = O\,(c.g.r)\,\bar{C}\,(r,g,t)$$

where S is the production of semi-finished good c going to production of consumer goods,and O is the amount of good c needed for the production of one unit of good g by process r.

We can also similarly consider the production of semi-finished goods for semi-finished goods. By a process known as matrix inversion (see any text on input-output economics) we can obtain the total amount of both direct and indirect needs of semi-finished goods for the production of consumption goods.

We now examine the stock of capital goods required for the production of our consumption and semi-finished goods.

We have

$$G\,(d,t) = E\,(d,g,r)\bar{C} + E(d,c,r)\bar{S} + E(d,d,r)T(d,r.t)\,dG/dt$$

where G is the total stock of capital goods of type d at time t,E is the stock of a given type needed for a unit production rate of consumer goods,semi-finished goods and capital goods,$\bar{S}$ is the total production of semi-finished materials both direct and indirect for consumer and capital goods, while

$$dG/dt$$

is the rate of change of the stock of capital goods, and is therefore the total production of capital goods.

Now,since $\bar{S}$ is a linear function of $\bar{C}$ and

$$dG/dt,$$

we have a simple linear tensor differential equation for G. The solution must be an exponential function of the form

$$G = \exp f(C,E;O,T)$$

or, since C is itself completely determined,

$$G = \exp f(W,P,E,O,T)$$

Finally we can calculate the labor demands created by the production of the consumer, semi-finished and capital goods. Without continuing with the details, it is clear that total labor demand is an exponential function of L, the labor demands for various skill levels for each product, and W,P,E,O,T.

Thus the total workforce, and therefore the total working age population must be totally determined by the length of the working day D, and W,P,E,O,T.

It should be noted in addition, that the coefficients E and O are not in reality time-independent, but in the case of raw materials, depend on the state of the surrounding ecosphere (its depletion relative to a given process) and thus on the entire previous history of P,W, and T.

We now examine the relation here outlined.

1) The evolution of the total population over time is completely determined by the evolution of the working age population, the death rate, and the rate of education of the various age and skill groups. The death rate is a direct function of the level of consumption (including services), while the educational rate (the amount of time spent in school) is a direct inverse function of the length of the working day. Therefore, the population is completely determined as a function of itself, W,E,D,O,T. Since E and O are simply descriptions of the technologies involved, P is essentially purely a function of W,T, and D $\frac{1}{m}$ the consumption levels, the choice of technologies and the length of the working day.

2) These three variables are not independent, since they are further constrained by the "boundary conditions" within which the stock of capital goods is historically fixed at the starting point of the planning period. Therefore, the choice of technological development determines within narrow limits the length of the working day and the consumption or wage rates.

3) The range of possible paths of development of the technologies is restricted to certain surfaces by the necessity that the path of evolution of the population be possible — that is, that the equations are actually soluble.

4) All variables of the economy, including the population, are expressible as tensor exponential functions determined by the development of technology.

## APPENDIX II
## ENERGY CONTENT OF THE BIOSPHERE AND THE SECOND LAW

An alternative formulation of the contradiction between the process of evolution and the second law of thermodynamics can be obtained if the overall energy content and radiation temperature of the earth is examined, rather than the energy flows. Given the situation in which a hot body (the sun) is put into radiative connection with a colder body (the earth) at the same time both are in contact with a third, still colder heat sink, (the rest of space), classical thermodynamics would arrive at the prediction that the earth's temperature would approach a steady-state value. This value would be that temperature at which the total amount of radiation received by the earth from the sun would equal that radiated from earth into space. In fact, the rate of growth of the energy content of the biosphere (including man) represents a deduction from the energy which would otherwise be radiated into space. Since, as the article, points out, this energy content is growing at an accelerating rate, the difference between the energy inflow and the energy outflow is also growing at an accelerating rate. Thus, the earth, which was once near equilibrium relative to the sun and space, is moving further and further away at an accelerating pace in direct contradiction to the second law of thermodynamics. Another way of putting this is that the radiation temperature of the earth is *dropping* at an accelerating pace (over the time scale of evolution). This is as thermodynamically predictable as the situation in which a pot of water, placed on a hot fire, turns to ice rather than boiling!

# Prospects for Nuclear Fusion Power

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The closest thing to a single solution for the world's many problems would be an unlimited supply of cheap, clean energy. The world could then feed and house its growing population, alleviate the mineral shortages that produce international tensions, clean up the long suffering environment, and enjoy a stupendous number of other benefits.(1)

The exciting thing is that cheap, clean energy is not an idle dream. Scientists right now are converging on the remaining technological obstacles that still keep us from this powerful solution to so many problems.

The source of this fantastic power is the process known as thermonuclear fusion. All of the stars, including our sun, create their vast energies by the fusion process. On earth, hydrogen bombs, which depend on fusion reactions, have convincingly demonstrated the potency of this source of energy, but many people do not realize that the same power that can be used for such horrifying destruction can equally well be used for human betterment.

Fusion does not depend on fossil fuels, which are limited and dwindling, but on fuels that are extremely abundant. Certain types (or isotopes) of hydrogen can be joined, or fused together, with a tremendous release of energy. For instance, the world as a whole has 8,300 Q of known and probably reserves of lithium, one likely fusion fuel when converted to the hydrogen isotope tritium.(2) Seawater contains another 21 million Q of lithium. Q is a unit of heat measurement equal to a billion billion BTU, or British Thermal Units. The entire world now consumes about a fifth of a Q each year. The situation is even more favorable when we consider deuterium, a hydrogen isotope that is also a fusion fuel. The oceans contain 7.5 billion Q of deuterium, enough to run the earth for billions of years. The procurement of deuterium from the oceans, where it occurs as one part in every 6500 parts of hydrogen, is comparatively easy and the water can be returned virtually unchanged to the oceans.

Fuel costs for fusion are almost completely negligible. Essentially every nation of the world possess these fuels. Thus fusion would eliminate for all future generations what has been a major cause of international tension and wars; the conflicts over the energy resources that are essential for the survival of industrial societies.

The fusion process is relatively clean — in sharp contrast to the polluting combustion of fossil fuels. Fusion does not release carbon dioxide or other combustion products into the atmosphere and it does not burn the earth's oxygen or hydrocarbon resources, which could be used as raw materials for many chemicals if they were not burned for heat. The extraction of fusion fuels from the land or seas would present a negligible impact upon the environment.

Another important advantage of fusion is that no radioactive wastes are produced from the burning of the fuel, although radioactivity is produced in the structure of the plant due to the neutrons generated in most fusion fuel cycles. For a given fuel mixture, the extent of this induced radioactivity depends upon the structural materials used. This selection is up to the reactor designer, and studies have shown that the amount of this radioactivity can be kept relatively low. In addition, the plant must be carefully designed to prevent leakage of tritium fuel from the reactor. Tritium, however, is one of the least toxic radioactive materials. Some common fusion fuel cycles are given in Figure 1 as well as the reactions required to produce or "breed" tritium.

The fusion process is also remarkably safe. A fusion reactor is inherently incapable of a "runaway" accident. In fact, the fusioning hydrogen gas or "plasma" is so tenuous that there is never enough fuel present at any one time for a dangerous nuclear excursion to occur.

Since no solid material can exist at the temperature

**Figure 1 Fusion Fuel Cycles**

| Reaction | approximate threshold plasma temperature | approximate average energy gain per fusion |
|---|---|---|
| $D + T \rightarrow {}^4He(3.5NeV) + n(14.1NeV)$ | 10keV | 1800 |
| $D + D \rightarrow {}^3He(0.82NeV) + n(2.5NeV)$ | 50keV | 70 |
| $\rightarrow T(1.01NeV) + p(3.02NeV)$ | 50keV | 70 |
| $D + {}^3He \rightarrow {}^4He(3.6NeV) + p(14.7NeV)$ | 100keV | 180 |

**Tritium Breeding Reactions**

$n + Li \rightarrow T + {}^4He$

$n + {}^7Li \rightarrow T + {}^4He + n$

range required for a useful energy output from fusion (about 100 million degrees C) the principal emphasis has been on the use of magnetic fields to hold the hot gas or plasmas from the walls. These invisible magnetic fields are hundreds of times stronger than what people usually experience using a household magnet. Other methods such as the use of electrostatic fields or inertial confinement (as when a solid pellet is ignited to fusion temperatures by a high power laser) are also being researched.(4)

The first fusion reactors will very likely operate using the deuterium-tritium (D-T) fuel cycle since the plasma physics conditions are easier to achieve than in any other fusion fuel mixture. Figure 2 and 3 are conceptual designs of DT fusion reactors.

The waste heat from such plants will about equal that produced in the most efficient fossil fuel or fast breeder power plants of similar size planned for the future. Figure 4 illustrates thermal energy conversion from a fusion reactor.

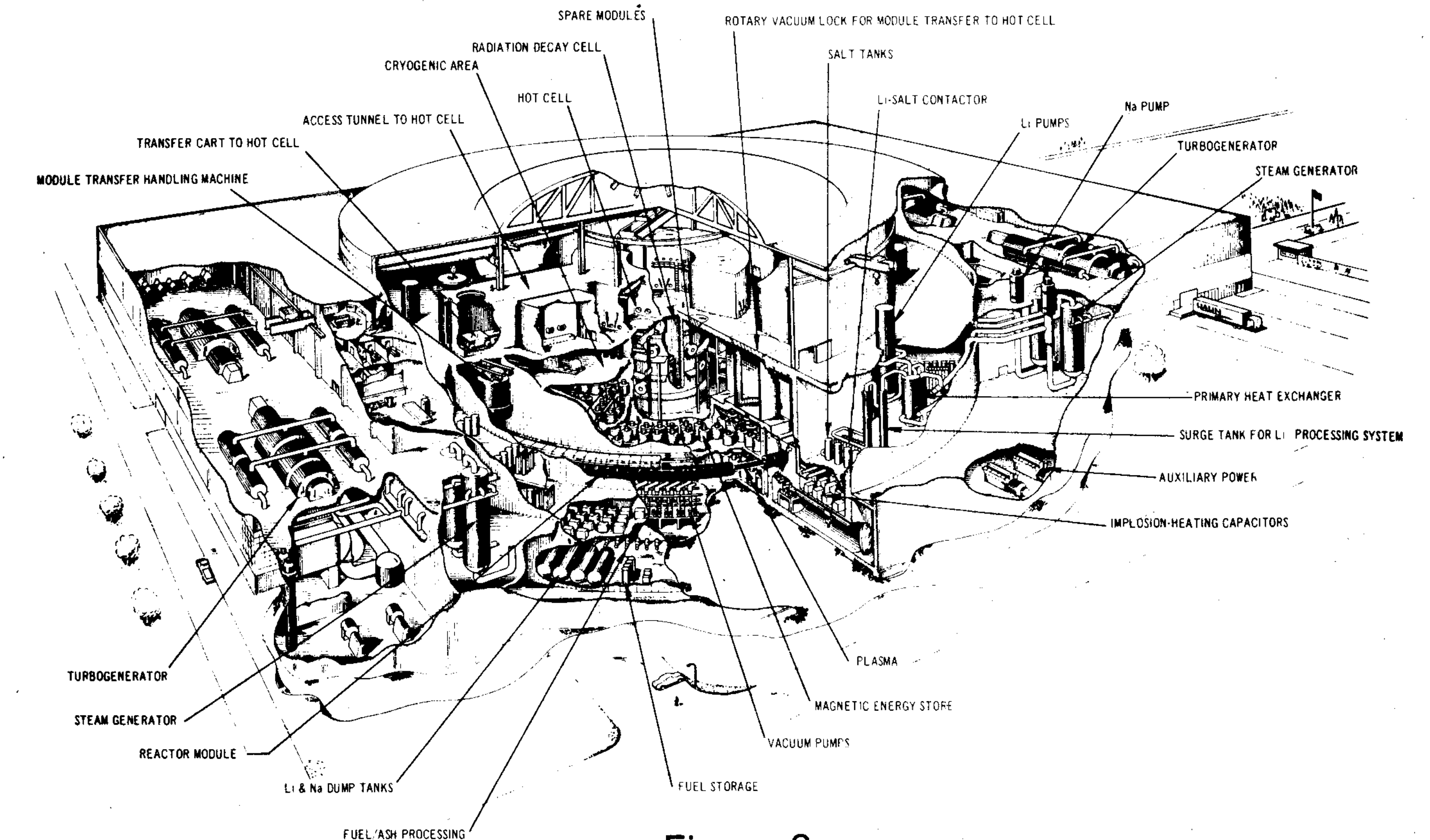

Figure 2

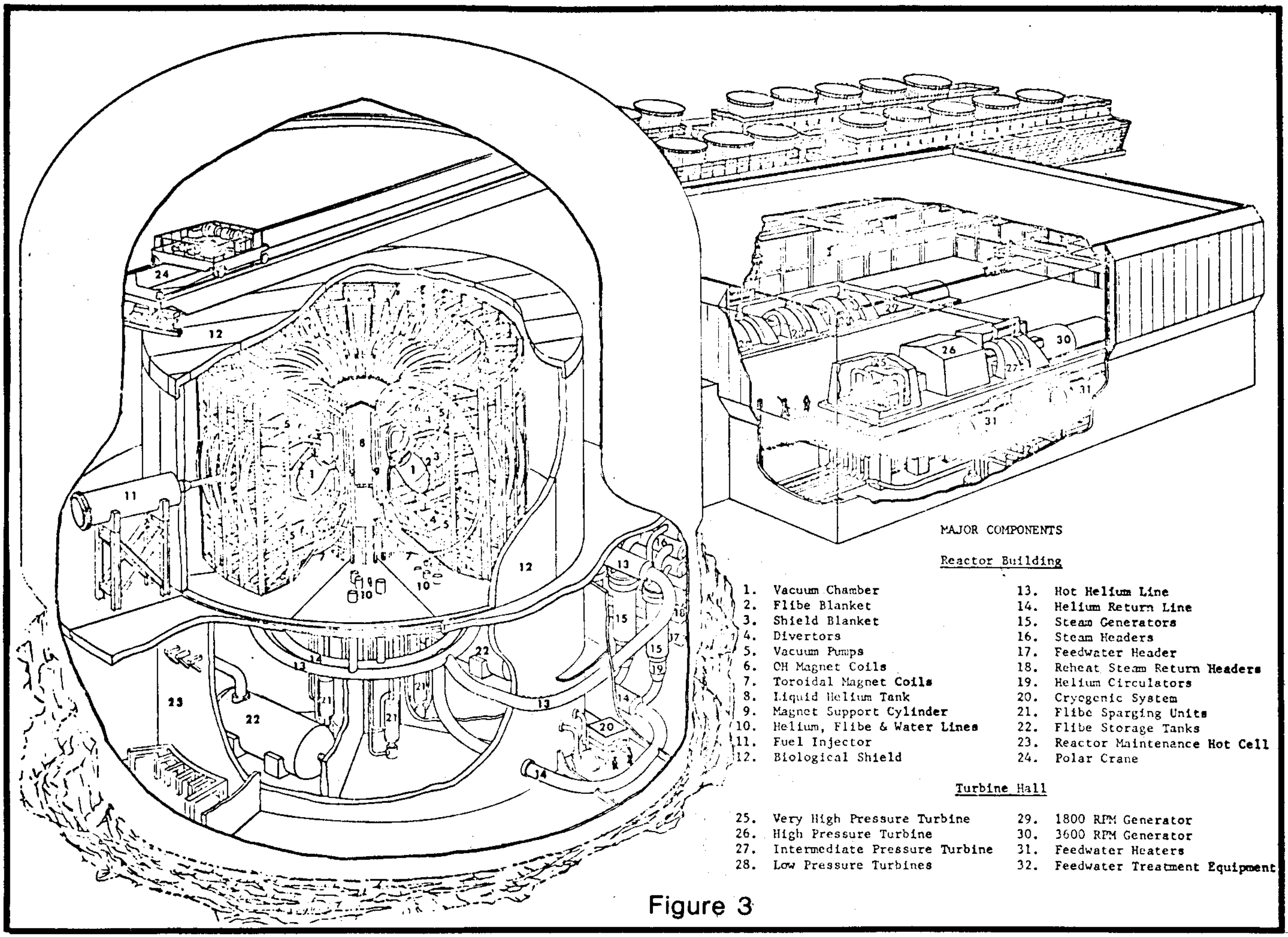

Figure 3

The environmental advantages and safety of fusion reactors may permit the siting of fusion power in urban areas where a good use could be found for the waste energy, such as the heating of buildings or the processing of sewage. As one moves towards the more advanced fusion fuel cycles the need for making tritium fuel from lithium in the reactor disappears and the number of neutrons produced progressively becomes less and less until it is insignificant.

As the fusion energy increasingly becomes available as charged particles rather than neutrons, the production of electricity directly from the ultra-high temperature fusion plasma at extremely high efficiencies becomes possible. Advanced fuel cycles and direct energy conversion are considered possibilities for second generation actors. At present, very limited work is underway on such possibilities due to the expensive and high risk nature of such research and development.

Over the last few years, the fusion program has entered a period of transition as we prepare to undertake the massive effort required to turn a laboratory research program into a major new energy source.

In a day when people spend hours of their time waiting for energy at the local gas station, a natural question is when will the abundant cheap energy from fusion be available? Unfortunately, fusion will not be here in time to relieve the present energy crisis — which results from having energy in the wrong form for existing technologies. You just can't burn rocks in your gas tanks even though we still have plenty of energy in the form of coal and uranium in the United States. The clearest warning for the present crisis came in 1970 when the rate at which we were finding domestic oil reserves failed, for the first time, to exceed the rate at which we were consuming oil. The current energy situation results from the inaction on the part of this nation to take anticipatory steps — for example research and development work on coal gasification and liquification.

The present energy problems are a precursor to more serious but equally predictable future crises. Ones that will involve the closely interrelated questions of energy supplies, material availability, and environmental degradation. Plentiful fusion energy would be a major factor in averting a future crisis so that you and your children could experience a good standard of living in a healthful environment. The development of a major new technology like fusion energy is expensive and the lead time is long, yet it may be needed sooner than many people are willing to admit.

To appreciate the steps remaining before commercial fusion power will be available to you let us look back and see how far we have already progressed. The inception of the fusion power program was in 1952 over twenty years ago. The accomplishments to date have been significant. The technologies for creating and studying million degree plasmas were developed, a new field of physics for understanding fusion plasma has evolved, experts in this new field of physics are now graudating from American universities, the barriers that appeared to exist for achieving the temperature, densities, confinement conditions necessary for a fusion reactor have all been broken in individual experiments, and recently fusion experiments with designs heavily dependent upon the new theories have operated as predicted. In fact, small amounts of fusion energy have been produced under controlled conditions in our laboratories — but far less than the amounts necessary to achieve net power. We now believe that there is no basic law of physics that keeps us from economic fusion power. Although many years of hard work have gone into these accomplishments, the cost to the American taxpayer has been less than the cost of a single moon shot.

Our next goal on the road to fusion power is to achieve all three of the essential fusion conditions — temperature, density, and confinement time — in a single experiment that produces net energy. There are many possible pitfalls ahead since physics and engineering uncertainties remain to be better understood. Yet we are confident that with adequate funding, solutions will be found to any problems that arise. We project that the much larger "energy breakeven" experiment will operate in the 1980-82 timeperiod. Recent analyses have indicated that by tailoring the plasma in the experiments in certain ways, "breakeven" conditions might be achieved in the late 1970's using the smaller experiments now under construction. An intensive effort to evaluate this possibility is now underway.(5) Figure 5 shows the "breakeven" plasma conditions for both the tailored "two component" case and the familiar Lawson criteria.

In addition to the plasma physics challenges that may lie ahead as we move towards fusion power conditions, extensive engineering developments must be carried out — for example in materials, superconducting magnets, plasma heating technology, neutronics, and tritium chemistry. Such work will enable experimental fusion power reactors (20-100 million watts electrical) to be operated in the mid and late 1980's and a demonstrated fusion power reactor to be operated about the year 2000.

The engineering and materials development for these long lead time systems will cost billions. The President's fiscal year 1975 budget request to Congress included a five year plan for the fusion program totaling $1.2 billion. A number of this magnitude needs to be put into perspective. For example, this amount is $200 million less than the cost of the new 2300 mega-watt electric power plant planned by Consumers Power Company for Quanicassee, Michigan. Even assuming a greatly reduced growth rate in the use of energy in the United

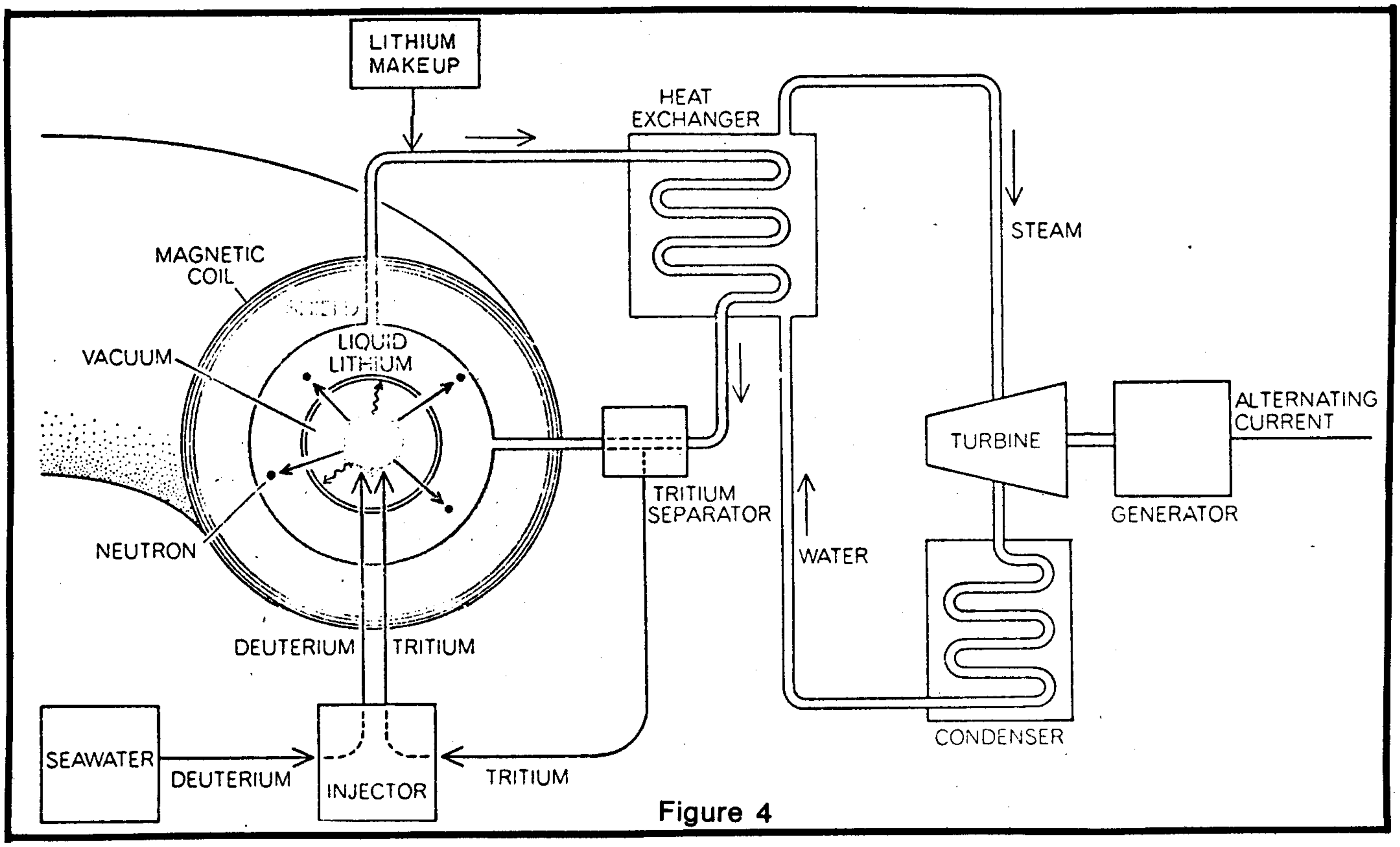

Figure 4

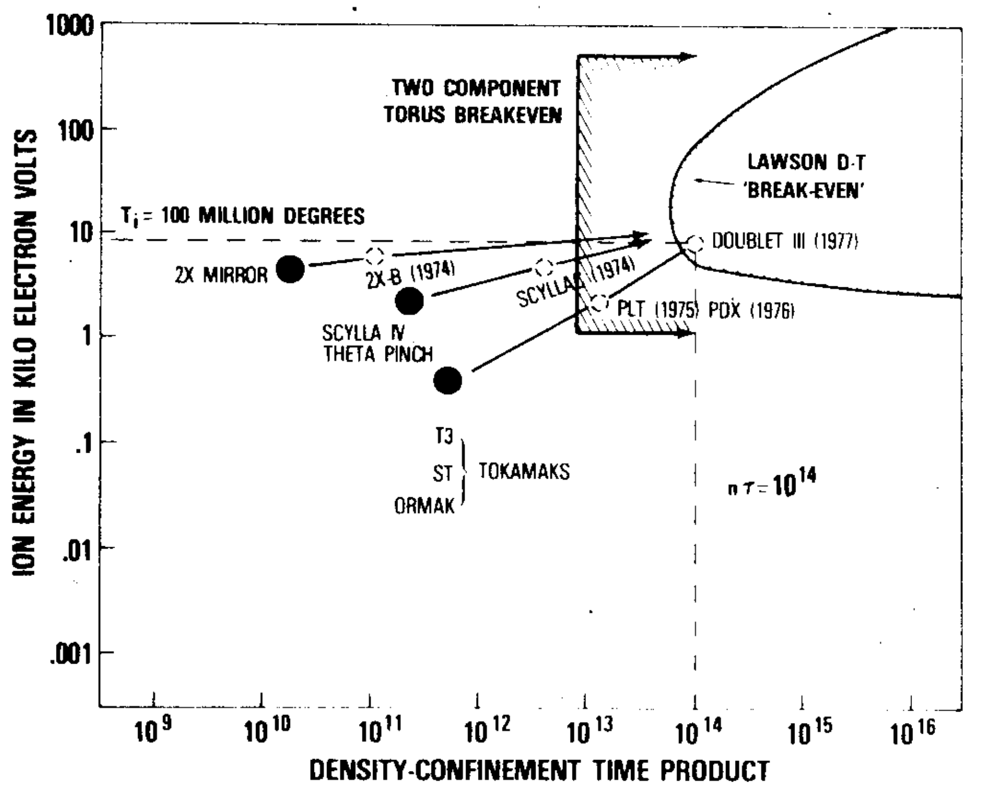

Figure 5 "Break-Even" Plasma Conditions for Fusion Power

States, more than 500 such nuclear fission power plants each as large and each at least as expensive will be needed by the year 2000. This is in addition to the large number of fossil fuel plants scheduled. The present budget of the AEC's Division of Controlled Thermonuclear Research is $56.8 million and it is anticipated that this budget will increase considerably this year.

The specialized manpower required for the initial stages of a rapidly expanding fusion program exist. There are now an estimated 1500 plasma physicists in the United States; the fusion power program employs only about 300. Engineers, chemists and physicists trained in the space,weapons and nuclear fission reactor programs have the necessary backgrounds to perform the projected tasks in fusion materials research, tritium studies, component development, and system engineering.

Fusion technology can do more than lead to a system for producing electricity. Fusion will also provide a unique means of producing large quantities of electromagnetic radiation, energetic charged particles, and high energy neutrons, which will yield important benefits to mankind.

A strategy for a liveable long-term future might include:

1. A stabilized world population.
2. A closed materials economy where wastes are converted into new raw materials.
3. New industrial and agricultural processes (including recycling), that avoid the undesirable byproducts resulting from today's widespread use of energy in the form of chemical compounds.
4. An abundant energy source that is highly compatible with the earth's environment.

Besides meeting need number 4 (abundant energy), fusion technology may help us to meet needs two and three by creating high temperature plasmas that are ideal for converting energy to forms that can be tailored to do specific jobs.

Recognizing the unique potential of fusion plasmas, my colleague, Dr. Bernard J. Eastlund, and I put forth the concept of the "fusion torch." The general idea is to use the ultrahigh-temperature plasmas, quite possible directly from the exhaust of a fusion reactor, to vaporize, dissociate and ionize any solid or liquid material.

The fusion torch might eventually make possible the steady-state economy, in which all wastes become raw materials for new products. More immediately, such techniques offer the possibility of processing low-grade mineral ores or producing portable liquid fuels by means of the plasma system.

The fusion torch could be used to transform the kinetic energy of a plasma into ultraviolet radiation or X-rays by the injection of trace amounts of heavy atoms into the plasma. The large quantities of electromagnetic energy generated in this way could be used for many purposes — desalting seawater, heat, and producing hydrogen. Such new industrial processes should be less likely to pollute the environment than traditional methods. Industrial processes based upon fusion technology are just starting to emerge and could come into widespread use during the next ten years.

Fusion reactors operating on deuterium-tritium fuel would produce large quantities of neutrons. Although one usually thinks of moving directly from nuclear fission reactors to pure fusion reactors, we could possible move through a stage where fusion-fission are combined in a single system to form a hybrid reactor.

Such systems involve the coupling of neutrons from fusion reactors with nuclei or uranium or thorium to produce a multiplication of energy and thus less stringent conditions for net power. In addition to generating electricity, the hybrid could provide fissionable material for existing nuclear fission power reactors during the years when pure fission power is phasing into our total producing system. Another use for the neutrons from fusion would be to reduce the problem of fission wastes. "From recent studies it appears that fusion reactors can potentially transmute most of the high level wastes from a fission economy into stable or short half-lived ash. However, the problem is extremely difficult and it will require considerable effort to assess fully the practicality of these ideas."

The fusion program in the United States involves government laboratories, private industry, and universities. In addition to the federal government, the public utilities are now funding a small but growing program in fusion research. The U.S. fusion program represents about one fifth of a close cooperative worldwide endeavor to meet a major problem of mankind. The world fusion effort can be divided into four parts — the largest is in the Soviet Union, followed by Euratom nations, then the United States and finally the rest of the world (principally Japan, Sweden, Australia and Canada). The cooperative nature of this program has been spearheaded by world conferences sponsored by the U.N.'s International Atomic Energy Agency. An expanded exchange of U.S. and Soviet scientists to work in each others' laboratories is now being undertaken to augment the already extensive mutual exchanges that exist between the U.S. and western nations. One can envision the time when space communications technologies are used to accelerate the world fusion power effort. This could be accomplished by connecting via sattelite the twenty major world fusion centers so that remote terminals in all laboratories would have access to central fast computers and TV communications would link the top world fusion scientists so they could interact directly, continually and quickly. In the United States next year we have planned a large computer facility with interconnecting links to all major U.S. fusion laboratories.

There is no substitute for energy — you must have it to be a strong person, a strong nation, or a strong and healthy world. Indeed energy is a weapon, as increasing numbers of persons are beginning to realize — and fusion energy is truly a weapon for world peace and betterment.

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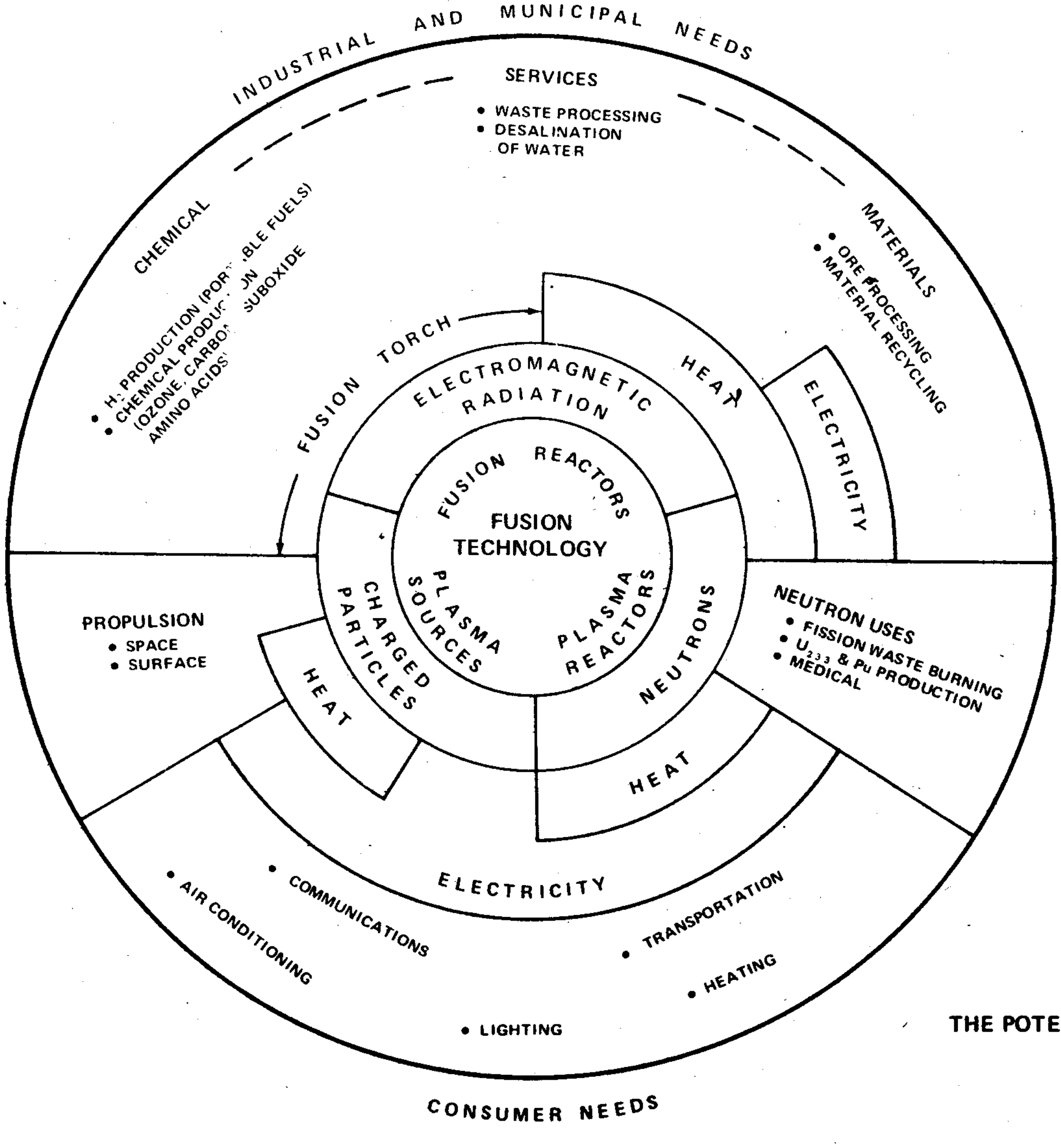

THE POTENTIAL OF FUSION

# Plasma Simulation and Special Purpose Computers

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## Prologue

The editors requested that this article begin with a personal statement as to why I wrote it. This I believe is a good idea. There are actually two questions here: why I wrote it, and why I am publishing it in a politically-oriented journal rather than a more sedate, traditional technical journal.

A primary motive for writing it was, of course, my interest in the technical issues involved in mammoth machine design, machine specialization and plasma simulation. A secondary reason was the Labor Committee's specifically inviting me to write it. Neither of these, however, are of great consequence for the purpose of this prologue.

The primary issue is politics. This prologue, as distinct from the technical article which follows it, is a political polemic. It is directed at my past colleagues in Plasma Physics, and the technical community at large. It is a call to arms.

To this point, let me speak a moment about my present politics: they are very much what they were in 1964 when I vigorously campaigned for Goldwater, and later chaired my college Young Republican club. Then as now I am vitally concerned about the freedom and dignity of the individual, and the need to be cognizant of human nature in the design of society. Then, as now, I am suspicious of detailed, centralized, *top down,* planning. Then, as now, I am concerned that due caution be observed in making changes so as to preserve the good, and not risk bringing the whole shebang down on our heads, for ignorance of some of the complex interdependencies of the system (an *ill-advised* change to keep *half* the world from starving could end up resulting in *all* the world starving by tearing apart what was left of a partially functioning system.)

Then, as now, I see the principal unsolved human problem as one of how to prevent big people from sitting on little people. That is, prevent more powerful or knowledgeable people from oppressing or taking advantage of less powerful or knowledgeable people. I mean this just as much on the small scale of a domineering wife oppressing a meek husband and her children, as on the large scale of a dictatorial government working people to death in concentration camps (as Hitler did.)

Then, as now, I see two principal parts to this problem: To a large degree the person who is oppressed is party to his being oppressed. He acquiesces to it; why? There is a psychopathology involved here. The other side of the coin is the problem of what causes the oppressor to oppress *where, in particular he could use the power he is using to oppress, instead, to help those he is taking advantage of to help themselves.* There is certainly a psychopathology involved here. There is also, in both cases, a lack of a *credible* alternative in the minds of the people involved (this ignorance being to some extent caused by, and certainly reinforced by, the psychopathology). Inventing and making credible a workable alternative is, therefore, the problem.

My position differs now from what it was then, only in my having a much better grasp of the real roots and ramifications of these problems. Remarkable enough, I find the same concerns among members of the Labor Committee. In particular, the Labor Committee is the only organization I have yet found, and I have looked extensively, which faces up in a solid way to both the real psychological issues which underlie these problems, and their full import vis-a-vis political and social organization. *I find their psychology to be sound.* I strongly urge the reader to acquire, and study until he understands, a set of the "Beyond Psychoanalysis" series which explains it. I am convinced that the Labor Committee has a firm grasp of the essential concepts required to develop and implement the credible, workable alternative we need, and they are the first group in the history of the human race to have this. I stress: what the Labor Committee has are fundamental insights, not a fully elaborated, detailed plan which is to be forcible impressed upon you. Such a plan is explicitly contrary to the whole fabric and structure of the alternative which is being offered. Appearances to the contrary are primarily a product of the psychological blocks and ideological prejudices which color your perceptions, and secondarily a product of the strain under which Labor Committee members operate, since they are fighting a very awesome and ruthless enemy.

The primary task at hand is not a political or economic revolution; it is a revolution in human consciousness — an awakening, and freeing from neurotic disablement (suppression), of each individual's creative self-consciousness. This surely sounds hopelessly idealistic. However, the more you grasp the reality of the underlying psychological factors, the less idealistic it will seem.

In the last six years I have been primarily concerned with the problem of developing the knowledge and technology necessary to successfully deal with the sorts of complex, interdependent systems which are characteristic of the psychological, social, ecological, economic, etc., problems that seem to beset the world.

I am *not* a member of the Labor Committee. Much of what they write puts me off, turns me off, and makes me think they are crazy and incompetent. However, try as I might, I have yet to isolate a *substantial* error on their part. Time and again, upon close enough examination, which is to say, upon my finally grasping what they are in fact saying, which is to say my being able to grasp from *their* point of view and understand how my point of view differs from theirs, *apparent* idiocies on their part have turned out to be errors on my part (*). In particular, the impulse to violently reject their assertions, with the expletive "crazy" seems to arise from my own psychological blocks and my own blind acceptance of ideological beliefs. (To find that my apparently reasonable and rational beliefs contained within them hidden and therefore blindly accepted arbitrary ideological positions has been quite a shock! I can guarantee you will find yours do also.)

I have been especially put off by the fact that all I seemed to get from the Labor Committee was a pile of *negative shit,* and *no humility,* and they seemed *closed-minded* to boot! All three of these — a positive attitude, an open mind, and a profound humility — are essential for good, creative scientific work, *and anything which is going to be done with enough sensitivity to lead to some good.* However, I am now convinced that these apparent deficiencies are a surface phenomenon. Excellent work also requires a certain hubris — a confidence that *you have the ability* to achieve the significant creative insight you are after, or to respond with the needed high degree of human sensitivity. It also requires being substantially *right* (*). The Labor Committee has all five of these: a

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If you are aware of a **substantial** error which does not fall apart under this kind of close scrutiny, I would appreciate your **writing it down** and communicating it to me (I stress writing it down because once it is out of your head **and** onto paper, it will almost certainly be clear that it is incorrect, insubstantial, or simply a manifestation of your own fears and psychological blocks).

Maintaining a humbly open mind and at the same time a hubristic confidence in the correctness of what you know is a promethean art of first magnitude — requiring full use of your creative self-sonsciousness. Wants of infantile egos and demands of internalized mother images are totally incompatible with the effective exercise of this ability. It can be done; all it requires is shedding neurotic attachments.

positive attitude (and positive program which they are actively pursuing), open minds, a profound humility and therefore human sensitivity, an appropriate hubristic confidence, and, hardest to accept, unassailable correctness.

If everything is so hunky-dory, why all the shit? There are a large number of interlocking problems here. For one thing, the most significant things the Labor Committee is right about are things *which the modern intellectual tradition has given up on ever being able to know*. Our having given in to this failure results in us having a *very strong* subconscious antipathy not just to accepting the ideas, but to even apprehending them to begin with. It hurts to even consider thinking about them. We subconsciously knew we were doing wrong when we accepted the prevelant views. The guilt for thus contributing to the debasement of our fellow men is overwhelming. This is exacerbated by the fact that both a substantially correct statement of exactly what is true in these areas, and a substantially correct demonstration of these things:

1) runs head-first into a number of other neuroses which are endemic to this society,

2) runs head-first into a large number of other, usually hidden, ideological biases of modern Western culture, and

3) is significantly more technical than the average liberal arts education equips one to handle.

Given this difficulty and these blocks, the most common occurrence is for a person to project his own internal situation onto the Labor Committee and (given that projection, quite rightly) exclaim, "You're crazy!"

The implications of what the Labor Committee asserts are awesomely frightening. The only trouble is, they are right.

From my experience, a notable example of an *apparent* Labor Committee error was their crazy assertion that practical fusion power systems could be operationsl within this decade. I *knew* that was wrong! *I had been in the field!* I did post-graduate work in Plasma Physics first under C.K. Birdsall at Berkeley (yielding an M.S.) and then at Princeton under John Dawson (*). It was clear to everyone involved, both at Berkeley and Princeton, that laboratory demonstration of feasibility was about 10 years away, and practical power plants were another 10 years away. I knew this was true; I was sure it was true; all the experts were in agreement. I was wrong. About 9 months ago, I realized that this belief *implicitly assumes current levels of funding!* In fact, I had seen no serious thought given to this issue; the idea of a real Manhattan Project-style crash program was always dismissed as foolish idealism (politically impossible), *and therefore not investigated.*

When a Physicist tells you practical fusion power is 10 to 20 years away, he is talking through his hat. No serious investigation has been made by the Plasma Physics community of the degree to which the program could be sped up by a *massive* investment (to the best of my knowledge, and the Labor Committee has been looking rather hard for such). (If you know of one, please communicate it to me.)

The reasons this situation exists are rather subtle, and are very important to this polemic. You might wonder if there is some kind of conspiracy among Plasma Physicists to cover up, conceal, or slow down their research. From my contact I am quite certain that each and every one of the people who is actually engaged in fusion research is quite serious and dedicated. He believes in what he is doing, seeing himself making a substantial contribution to a great new age of plenty, sometime in the not-too-distant future. He is doing the best he can *within the framework he has been provided.* There's the rub, and there is where politics directly impinges on our problem. *The framework that is being provided is not adequate* (*)!

When I was in the field in the late Sixties it was clear to my colleagues that neither basic Plasma Physics research nor Plasma Simulation were receiving anything close to their *appropriate share* of the small amounts of monies being spent. We had the following ludicrous situation: the original large-scale experiments of the early Fifties failed to perform as expected by a whopping 5 orders of magnitude (factor of 100,000), and even after almost 15 years, eventual laboratory success with such experiments *still* appeared to be 10 years away; yet, the AEC continued to sternly maintain its policy, in the face of vociferous objection by at least the physicists of my immediate acquaintance, of *not* spending a substantial amount of its controlled fusion budget on relatively inexpensive small scale Basic Research (both physical and computational experiments) *to develop the basic knowledge that was clearly lacking.*

Why? Those I knew in the field at the time seemed to attribute this idiocy to one or another kind of incompetence on the part of the policy makers.

It does appear that one must either believe some sort of "incompetency theory" or believe some sort of "conspiracy theory." The issues vis-a-vis the nature of research and development involved in this resource allocation problem are simply too basic and elementary

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*I moved to Computer Science,where I an now a PhD candidate, due to a mismatch between my creative design talents and interests, and the demands of the present style of physics research.

* This is a classic example of controlling people by controlling their environment — a standard operating procedure of the more sophisticated oppressor. To my old colleagues in fusion research, let me pose the question raised above with regard to oppressed people acquiesing to their oppression: why have you stood for this situation? Will you continue to stand for it?!?

for me to be able to easily swallow the incompetency theory.

So let's consider for a moment the conspiracy theory. The idea that people have been conspiring to affect the policies of this country for their own special benefit in this sort of way, irrespective of the public good or safety, *and therefore actually affecting them,* sticks in my craw. I do not want to believe it, and at first thought it seems awfully unlikely. But then, conspiracies of a slightly different type, like the Tea Pot Dome scandal and the Bobby Baker scandal seem to be relatively commonplace. So I can not dismiss it entirely, and I think the evidence warrants an investigation.

More importantly, effects much like those of a genuine cloak-and-dagger conspiracy, effects such as we see, can come about in a much less clandestine way. Influencing policy is, after all, what politics is all about.

The issue at hand is your political involvement, as a member of the technical community. Either the people presently making fusion research policy, and those who strongly influence them, are incompetent and should be removed, removal being a *political issue,* or there is a conspiracy of one sort or another (anything between a normal, above-ground, political conspiracy and a real cloak-and-dagger-style conspiracy will do). Like it or not, defeating this conspiracy, to the extent it exists, is a *political issue* [*]. No matter how you slice it: *politics! And, because of your special knowledge, the need for you to be involved!*

As an engineer and a scientist, I should like to avoid politics. I am sure you feel the same way. However, rather to my chagrin, I find that by the very nature of my profession, I am irrevocably involved in the politics of this critical time. This is on two counts, one of them touched on in the last sentence of the above paragraph and both elaborated below.

It has recently become fashionable to point out, as criticism, that technically trained people's competences do not extend beyond their particular narrow fields — in this view they are not any better qualified to speak out on important national and world political issues than the average man in the street. There is a lot of merit in this observation. *However,* for the present situation, this criticism would be a red herring. *Our technical competences have a very direct bearing on all of the fundamental issues involved in the present crisis.*

*The question before us is whether or not we will use our powerful technological muscles to solve the [apparently] large problems confronting us, like the so-called energy crisis* [*], *or whether those whose political and economic interests are served by accepting the idiocies of the Forrester-Meadows "Limits to Growth" analysis will win, and we will give up [letting, among other things, the Third World starve].*

Politics is often said to be the art of the possible — a good politician does not attempt the impossible; he seeks out and implements the possible. The critical point is that technology is *also an art of the possible — it is the art of making the impossible possible,* of making what was impossible yesterday possible today.

We in the technical community are therefore irrevocably involved in politics, *and we have an opposition.* The question is not one of engaging in politics or not, but is rather one of dropping the ball half-way through or not. In the last fifty years, we have developed the technology necessary to develop needed *new* technologies at the drop of a hat. As we all know from bitter experience, rather than seizing this capability and wielding it against, for instance, the massive environmental problems that began to emerge in the middle and late sixties, as we wielded it against the far less important problem of reaching the moon, this country's policy makers have been progressively dismantling it and throwing it away! This is politics! These are the politics of the opposition. *These are the politics of those whose interests would be severely damaged by making possible things like fusion power that have heretofore been impossible.*

This dismantling of the technological establishment, and the attendant propagandizing that *technology* itself rather than resource allocation policy is at fault (viz., "Limits to Growth"), is not a trivial fact, it actually touches the very core of our humanity.

It used to be fashionable to believe that there was something special which qualitatively distinguished human beings from "mere animals." The earliest versions of this belief were mystical garbage, quite deservedly superceded by more recent, rational, distinguishing criteria. The most significant recent version of this belief distinguished man as a *tool maker.* This has, of course, been demolished in the last few years by observations of other animals in the wilds *making* primitive tools. Language ability has also sometimes been thought to be a unique, distinguishing characteristic. Here again recent advances have demonstrated that chimpanzees are capable of learning, using and passing on to their young special languages of significant complexity. (Languages of *man's* invention, though, you will note.) More and more it has come to appear that we

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[*] We are truly fortunate to be living in a society where we can have realistic hopes of winning primarily through political measures rather than primarily through military measures; every effort must be expended to keep it this way.

[*] There is, by the way, a **real** energy crisis. It is how to generate, deliver, and effectively utilize five times more power so the rest of the world can be raised to the standard of living of the 6% that now uses 30% of the energy, and then generate at least twice again as much (net increase of a factor of ten), because even the U.S. living standard is inadequate for more than half of our people!

differ from other animals merely in the *degree* to which we have various characteristics. Desmond Morris would have you believe that you are *just* another variety of ape, naked at that.

This, however, overlooks (by virtue of not seeing the forest for the trees) the *most striking* distinguishing characteristic of man. Man is not merely a *tool maker,* he is a *tool inventor,* but not *just* a tool inventor: he *systematically* and *self-consciously* (that is, in response to a perceived need) develops new kinds of tools. Man is a *systematic tool inventor.* As a human being you have the ability to self-consciously decide that a technique you are presently using is not satisfactory, and, *motivated by this recognition, create a better one* * . In this you are unique in this world, no other animal can do this. We can assert this uniqueness with a great deal of certainty because the creation of new kinds of tools, upon the perception of a need for them, is the active mechanism behind a self-developing process: a good "vicious circle," if you will. The more new tools we develop, the more new things we are able to do. These new activities give rise to the need for even more new tools. (Of course, the first set of new kinds of tools do not just give rise to the need for the next set, they also facilitate the next set's creation!) This is an explosive process. (It is in fact exponential, because the more effective present tools are, the faster we see the need for, and can invent, even more effective tools). Therefore, it is not necessary to hunt around carefully to see if there might not be a few isolated chimps somewhere out in the wilds who engage in systematic tool inventing behavior in response to needs they perceive, because if there were, they would not stay a small isolated group very long! †

The most striking difference between human society and primate society (and all other animal societies) is that mankind has, over the ages, *repeatedly* used this self-conscious creative ability to develop progressively more and more sophisticated and powerful technologies, *in response to a need for them.* Therefore, the problem of the downturn in investment in research which began in the late sixties, and the present "popular reaction" away from technology, is not a small one, nor an insignificant one. The lack of development and application of our technologies, and in particular our ability to create new technologies to solve new problems as they arise, touches the very essence of our humanity, in addition to destroying the only possibility we have of defeating the problems that now beset us.

*We must speak out now! Technology is taking the rap for the failures of the resource allocation policy makers! We must organize politically to change these politically determined policies!*

I urge you to collaborate with the Labor Committee on this, as I am, *whether you can subscribe to all of their policies or not.* They are the only organization with both the insight and the moxie to make a significant dent in this problem. The more you come to understand the magnitude and roots of the real problem here, the more you will understand that this is the case.

Here again, if you know of an alternative, please communicate it to me. Some bogus alternatives I already know about are the following: "The Committee for the Future," headquartered in Washington, D.C., which publishes the "New Worlds Newsletter," and produces "SYNCONs." They *sound* very good, mouthing exciting phrases, such as:

"Although destitution still torments us, scarcity *could* be replaced at last by abundance as the central condition of human life. There *are* ways to provide adequate food, housing, shelter, medical care, education. But these options are not being exercised." [1]

This is marvelously correct. However, they show a complete lack of appreciation for the political, *economic*, and especially *psychological* realities of the difficulties and possibilities they rightly identify. They seem to premise their activities on the assumption that this world's leaders, in particular this country's leaders, are *unaware* of the technological alternatives to "Limits to Growth." This is hogwash.

Another group, with a "weightier" publication, is the "World Institute Council" in New York City which publishes the quarterly journal "Fields Within Fields," billed as "A Quarterly Forum for Ongoing Creative Thinking about Solutions to Mankind (sic) Problems" (quoted from the front cover of issue No. 11) — a hundred pages of fuzzy thinking every three months! Here again they *sound* good, quoting the statement appearing on the back cover of all three of the issues I have (emphasis added):

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*This is not at all a trivial fact. This ability is your creative self-consciousness. It is a very significant thing indeed. It is instructive to note that a list of things known to interfere with the use of this ability is identical with the traditional list of the seven deadly sins (lust, avarice, envy, etc.). Further, this analysis of your essential humanness is confirmed in detail by the psychoanalytical developments and practice of the Labor Committee (of which this analysis is an integral part).

† But what about **small isolated stone age human cultures** which still exist? Why do they still exist, and might there be a comparable chimp culture we do not happen to have come across? This is certainly a substantial hole in the above development **as presented here.** Developing the argument which plugs this hole would require several pages and would require the reader to grasp **all** of the most essential conceptions upon which the Labor Committee is founded; it is beyond the scope of this paper (but I urge you to pursue it). If the issue bothers you, let me note the following ***striking*** characteristics of stone-age human cultures — children of such cultures are indistinguishable from our own children in their ability to become good scientists and engineers. Not so with ***chimp culture*** children. The ***main thrust*** of human culture as described, the peculiarities of small numbers of backward groups is of little significance.

(1) pg. 1, New Worlds Newsletter, Phase II, Vol. II, No. 1, January, 1974.

> "The World Institute Council is a nonprofit research and educational institution serving the public nationally and internationally. It counsels government bodies and other educational institutions,supports research in human ecology, and publishes and disseminates such works and ideas as it believes will lead to solutions to the urgent problems facing mankind. To this end it is dedicated to encouraging the establishment of a World Institute — an international, interdisciplinary body of the world's most gifted people having access to the most modern information handling technology. Such a body would work together symbiotically,linking the best of mankind's thinking and *ultimately releasing creative potentials so powerful that they will be capable of bringing about a new gestalt wherein mankind will come to learn to live in change and,as a result emerge to a new level of awareness.* In essence the World Institute is conceived of as a kind of world brian by means of which man can emerge to his next stage of evolution; as it develops a methodology for resolving the most pressing of the world's currently preceived problems,the World Institute would be providing a feedback to the mankind body that *will allow man to change himself and, though an understanding of field theory concepts* to emerge into the holistic, comprehensive being he must become if he is to have any chance of surviving the present age of hydrogen destructibility."

*Great!* The only trouble is, this "new gestalt" so glowingly spoken of, already exists, and its development has a several hundred year history, of which the authors included in the issues I have, seem to be totally unaware. Worse yet, the consequences of the gestalt run wildly counter to the interests and organization of the present world power structure. The World Institute Council clearly seems to suffer from the same lack of grasp of the real political, economic and psychological issues involved here as the Committee for the Future.

There are also, of course, the people around Buckminster Fuller and his "anticipatory design science," who suffer from all the same problems. Two other notable groups who are avowedly out to save the world, and who are building "World Plan" centers and the like are the "Transcendental Meditation" societies of "Maharishi Mahesh Yogi" and the Divine Light Mission of "Guru Maharaj Ji." (These two, and others like them, at least show *some* appreciation for the depth of the psychological issues involved!)

The majority of the people participating in these organizations are surely good, and well-intentioned. I know some of them. However, *good intentions are not enough — vast numbers of human lives are at stake.* I used to think organizations like these had at least *some* merit. They each after all have some of the right ideas. The net effect of so much partial good must surely be a net plus for humanity. The only trouble is, there *is* an *opposition,* and for the purposes of this opposition, organizations such as these can serve as "countergangs" — they siphon off aroused, well-intentioned people's efforts into things whose impact can be controlled or minimized: things which just don't quite cut it as far as the real problems go, or things which are, in net effect, counter-productive. In some circumstances, countergangs can be used directly against organizations which have not yet been safely domesticated.

This term, "countergang" was coined by Frank Kitson, one of Britain's top counter-insurgency experts, describing the technique he originally used in putting down the "de Mau Mau" in Africa. His first book, "Gangs and Counter Gangs," Barrie and Rockliff, London, 1960, describes his early development of the idea. His more recent book, "Low Intensity Operations: Subversion, Insurgency and Peacekeeping," Stackpole, 1971, $9.95, may be more significant. In the forward (pg. xi), General Sir Michael Carver describes the book thus:

> This book is written for the soldier of today to help him prepare for the operations of tomorrow. It will be of greatest possible help to him and I hope it will be read by all those concerned with training the Army.

On page 25 in the first chapter, in discussing the reasons counter-insurgency training is important in the seventies, Kitson says the following:

> If a genuine and serious grievance arose,such as might result from a significant drop in the standard of living,all those who now dissipate their protest over a wide variety of causes might concentrate their efforts and produce a situation which is beyond the power of the police to handle. Should this happen the Army would be required to restore the position rapidly.

[Why does Brigadier Kitson propose that *legitimate* grievances, in a democratic country, be put down with military force?] This topic of counter-gangs and counter-insurgency is probably best dealt with in the April 1974 issue of this journal.

My polemic about the necessity of your *effective* political involvement is not complete without mention of what I see as the fundamental political issue. The present, and historical, primary resource allocation policy is that an investment can be justified only if it results in the relatively direct production of enough commodities (or their equivalent) to replace the commodities used up in making the investment. On the surface, this seems like an undeniable, a priori truth. If this condition does not pertain, you will go broke!

However, observe that a consequence of this policy's rigorous application is that an old investment can not be replaced until it has *entirely* paid off its initial cost, *regardless. The precarious position of the present investment in fast breeder reactors is merely an extreme example.* An important alternative, or augmentation, to this investment policy, which we are familiar with in rapidly advancing high technology fields, is the justification of a development *on the basis of what further developments it enables, as opposed to what it merely directly produces.**

Against the proposition that we immediately develop fusion power, it has been asserted that we have an *enormous* investment in fossil fuel energy technology, which we can not simply discard. Why can't we? Whom would it hurt? Certainly the *users* of energy would not be hurt because we would be replacing the old with a new, non-polluting, more abundant, and much less costly to operate technology.

*The issue is in whose interests the world is to be run: The interests of those who presently own it, or the interests of humanity as a whole* (including you and I).

The burden of proof that the interests of humanity as a whole are, at the present time and in the future, best served by the avid pursuit of the (fragmented) interests of those who *own* it, is on the part of those who would assert this. I have yet to see anything other than hot air, fearmongering propaganda, and hysterical denial of reality in support of this proposition, which is presently in effect as basic policy. The only compelling arguments I know were applicable *in the past,* but are *no longer applicable,* because of the present *high level of our technological development,* and because *this development is able to progress at an ever increasing rate.* Here again, if you can contribute some light to this issue, communicate it to me.

It can be argued, with considerable merit, that whereas the above analysis and criticism is valid in the abstract, experience has shown that the avid pursuit by individuals of their special interests, when coordinated by the freedoms, ideals, and safeguards characteristic of this country, *works a whole lot better than bureaucratic socialisms.* This is in fact quite right. The Labor Committee agrees with this, and I agree with this. If I thought the means to avoid the bureaucratic tar pit were not at hand, in the Labor Committee's new, basic insights, I would not be involved. The problem goes even deeper than bureaucracy, however. The fact is, for the typical heteronomic individual (as opposed to the atypical "self-actualizing" or "creatively self-conscious" individual) of modern society, our present dog-eat-dog system is very nearly optimal, the present slide toward fascism included. If other-directed people were all there could be, there would be no reason to hope for, let alone struggle for, something better.

In my judgement, the creative synthesis achieved by Lyn Marcus in the late Fifties, as reflected in "Beyond Psychoanalysis", puts a capstone on the basic conceptual development whose lack has prevented us from being able to solve clearly identified, long standing social ills. The roots of these ills are very much problems of insanity (in its mild forms called neurosis) as asserted in my opening comments above about oppressors and oppressed. What appears to me to be *in hand* is not a detailed prescription for how to solve all of these ills, but rather is a set of basic new conceptions and new points of view which are required for us to be able to generate the equivalent of such prescriptions. I say equivalent because the solution to a large, complex, changing problem can not be a simple (static) prescription but must itself be an equally large, complex and dynamic thing. Such solutions are not *in hand,* they are merely *at hand.* Your help is required to bring them into being.

If you have ever felt we live in an insane society, you were right, and now is the time to act. If you have ever wanted this to be a world where every individual has the right and the resources to develop his potentials to the fullest, in particular his potentials to make creative, sensitive, helping contributions to the welfare of his fellow man, now is the time to act.

From a number of sources I have received the caution that I should be wary of the Labor Committee: "They are unscrupulous Commies (and you know how unscrupulous the Dirty Commies can be [just ask the people who own CBS]. They will use you and throw you away!" This is quite untrue. It is even ludicrous: it is a projection of the characteristics of the masters of the present system onto the proponents of the alternative.

A person who expresses this fear is unaware of a key point: the Labor Committees is not *primarily* an organization. It is *primarily* an idea. It is an idea which has recently been brought to fruition, after centuries of development. It is an idea whose time has come. *Note: An idea whose time has come, and which is correct, can not possibly let you down, only you it.*

As a member of the human race who has become aware that all is not right with the world, it is your responsibility to do what you can about it. One of the things, and I believe the most effective thing, you can do about it is study, until you thoroughly grasp and can hence verify, the idea that is the Labor Committees (taking full cognizance of the psychological difficulties 'twixt you and understanding discussed above). To the extent you judge the idea to be valid and appropriate you can and must organize around it (with full confidence that it will not let you down). Furthermore, you must demand that the individuals of the *organization* called the Labor Committee (as distinct from the idea) do the same, to the highest standards. To the extent you find the idea to be invalid or inappropriate you can and must develop your criticisms and *positive alternatives*

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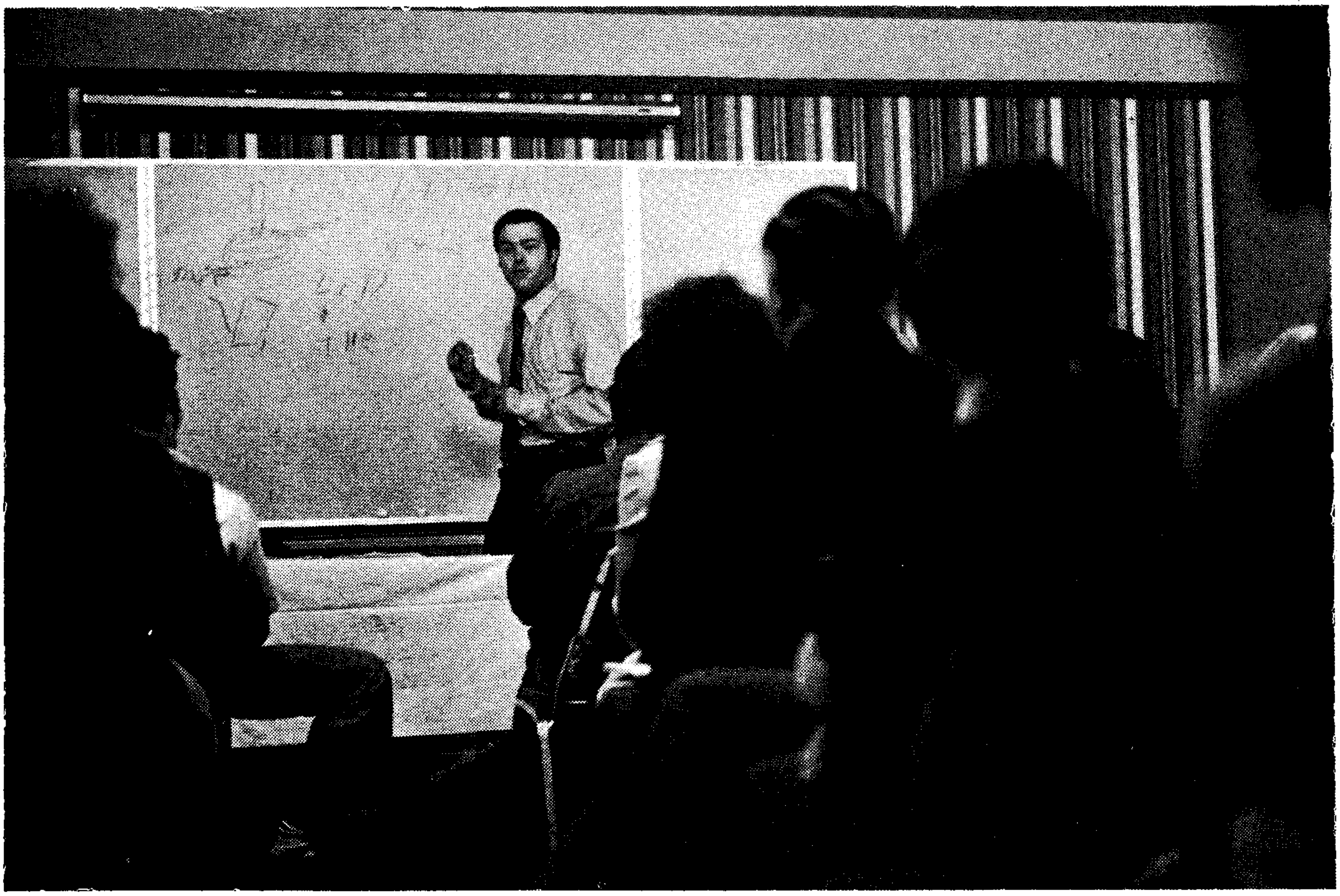
*The above statement of the present resource allocation policy is a dangerous over-simplification, used strictly to illustrate this point. A more careful look at the global policy of major investors, as for instance in "The Rich and the Super Rich" by Ferdinand Lundberg, Lyle Stuart, N.Y. 1968, finds that the issue of maintaining and extending control and power usually supercedes the mere requirement that a profit be made. This is seen most clearly in the early industrial development, the age of the "robber barons," in this country. This alternative policy is of course simply a variant of the above-suggested alternative of justifying an investment by what it enables you to do in the future (what new **power** it gets you) rather than just by what its immediate direct return is.



(preferably on paper) and demand that the Labor Committee take cognizance of them.

The future of the world is in your hands, my hands, and our neighbor's hands (like it or not), not the Labor Committee's hands. The idea that is the Labor Committee has only as much power as awakened, concerned people give it. We will either be involved effectively and for the good, or the potential for a sane, humane society that is within our grasp will be lost.

## I. Introduction

The remainder of this paper is a technical discussion of the issues involved in the construction of *Mammoth, Special Purpose* computers for plasma simulation. Its purpose is to make the case for such, to the extent it can be made with the resources I have available. Grants for more complete studies are being sought. Individuals with some competence in pertinent areas who are interested in these problems are requested to get in touch with me at Yale.

The Atomic Energy Commission's present policy, as explained to me by Dr. Bennet Miller of the A.E.C. [2], is to specifically *not* develop special purpose machines for Plasma Simulation. He stated that they feel they have a known job which can be done with existing computers. Rather than investigating the special purpose machine alternative (or supplement), their policy is to supply their people with all of the conventional machine time they need. This is justified on the grounds that if they diverted money resources from production computing to machine development, they might end up with a neat machine in a few years, but would not have solved the problems they know they need to solve, and they *can* solve, if they simply brute force the problems with existing machines.

When this was explained to me, I asked if the resource scarcity problem was not more one of Plasma Physicists to participate in the effort than simply dollars. He said no, he would not expect the personnel needs of such a project to seriously impact the time of the presently fully occupied physicists, it would involve primarily computer scientists who are not now involved in the fusion effort. In this judgement he is correct. I asked the question to confirm his implication that the policy against building special purpose machines was based strictly on a dollar resource limitation.

This policy is incorrect, and should be changed. If the factors to be gained through specialization of hardware were small, like factors of two or three, the policy would have *some* justification. But the potential gains are not small; they are between 50 and 500! To give you a feel for what factors of this magnitude mean, consider a project that was a disaster, where development took four years and which resulted in a gain on the low side, namely 50. Consider equal expenditures on this project for five years, and on conventional computing for five years. Even with the disaster, you get *10 times* more computing done in your 5 years! In 6 years you have almost 17 times as much computing!

My criticism goes a little deeper than just the dollar

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(2) Deputy Assistant Director for Research, Division of CTR, on the phone, September 18, 1974.

issue. I seriously doubt that the A.E.C. is actually following through on the policy of supplying all the needed computing on conventional machines. This is not indicated by my recent contacts. In particular, in his paper "Computer Applications in Controlled Thermonuclear Research" in the A.E.C. Special Report on Fusion of the fall of 1973, John Dawson stated, as *essential* to a fusion program for practical power production in the late 1990's, the establishment of one *or more* special purpose computer centers for controlled fusion research, with machines of the scale of the new Texas Instruments pipeline computer. What is in fact being implemented is *only one* computer center, with a *substantially* smaller computer (a machine of the scale of a CDC 7600)[3]. Furthermore, Dawson also indicated a need to run three dimensional calculations with grids of about 100x100x100, and 100,000,000 particles. It is not practical to run problems of that scale on any existing machines, except possibly the Texas Instruments machine.

I am therefore explicitly critical of the A.E.C.'s present computing policy. The primary purpose of publishing this article in this context is to substantiate the claim that the A.E.C. is not presently doing its job, if its job is in fact the *publicly avowed* objective of pursuing the public good (as opposed to the more likely job of maintaining the special interests of a few select individuals).

I first briefly present the case for Plasma Simulation for those of you who are unfamiliar with the field (and because there is still some contention in the field, mostly between the Physicists and their A.E.C. supervisors, about the relative value of simulation). I then present the general case for special purpose machines, and then discuss the present simulation algorithms in general, and focus on one class to analyze in detail, discussing a computer architecture which is optimized for this class of simulations.

I specifically recommend that *Mammoth, Special Purpose* computers be developed for Plasma Simulation. It is essential that these be developed in the same way that special purpose hardware for Plasma Physics research, like Tokamak's and Lasers, is developed, that is, mostly by, and entirely under the direct supervision of people who will be responsible for their use in controlled thermonuclear research (CTR). [4].

It is important not to confuse this issue with that of building mammoth, *general purpose* machines. Almost all of the speed that can be squeezed out of the present silicon transistor switching technology within a *General Purpose* architecture has *already* been achieved. See section III below for what is to be gained by specialization.

I recommend that a reader who is unfamiliar with the field read sections VI, VII and VIII next, as they provide a basic introduction to the problems which underlie the sections which immediately follow.

## II. Why Should We Simulate?

Why should we simulate? This is nothing less than the question of the relative value of calculations and other theoretical work in engineering design, as compared with experimental "cut and try." In the author's experience there is really no issue here. It is brought up only because there has in the past been considerable resistance to the "new" idea of direct simulation. This resistance has been partly due to a lack of understanding that simulation is a direct extension of the traditional mathematical modeling techniques of theoretical physics.

Historically, engineers have found, whereas "cut and try" works, and is in some cases the only effective way to get the numbers needed, it is generally the most expensive technique, to be used only as a last resort. In a computation, you make an analogue of a physical system. This analogue is generally made out of components that are cheaper, more easily re-useable for entirely different experiments, and more easily reconfigurable for investigating significant variations of parameters and approaches in your given experiment. Experiments done by calculation are therefore generally both cheaper and more versatile than real experiments.

Two issues, then, determine whether you do a computational experiment rather than a physical experiment:

1)Can the computation be done at all, or is it too large or involved for the present state of the art of computing equipment?

2)Are the components in the computational analogue, in fact, effectively cheaper than the real components?

In the case of digital simulation, as in Plasma Simulation, the first question here is, "How large a machine is it practical to make at the present state of the art?" The second question is, "How much does this machine cost?" As everyone connected with the field knows, the cost of computer hardware is falling rapidly, and shows every indication of continuing to fall (relative to the cost of everything else, that is). At the same time, the size of machine that can be built is increasing, because components are continuing to get smaller, and their reliability is continuing to improve.

What is the situation with Plasma Physics? Can we in fact do significant simulations at acceptable costs? The

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(3) as defined in the specifications let for bid, LLL-SE-72-2, LLL-SE-72-3, and LLL-SE-72-4.

(4) According to Dr. Slotnick, the designer of the Illiac IV (in a talk given at the ILLIAC project at AMES Laboratory in California in the summer of 1972), a major reason for the Illiac IV's problems was his group's not having enough in-house expertise to be able to evaluate the claims and approaches of the people to whom contracts were let to build it.

answer is an unqualified affirmative, and because costs are dropping, the scale and significance of simulations we can do is increasing. *Simulation is not only feasible in fusion research, but in many cases simulation-based theoretical understanding is the only effective understanding achieved or likely to be achieved.* Specific comments vis-a-vis simulation in Fusion research, and recommendations for an immediate sizeable increase in expenditures in the area were made by John M. Dawson in a paper titled "Computer Applications in Controlled Thermonuclear Research" in the A.E.C. Special Report on Fusion, Fall 1973.

For the reader unfamiliar with the field, it bears mentioning that the basic physics involved in the CTR problem is completely known, "in principle" (*). This means that everything could be computed if we had machines which were large enough. We however, do not and will not, probably ever. Effective simulation is therefore dependent on high quality theoretical insights which abstract, for direct simulation modeling, just those qualities of a Plasma which are essential for the given phenomena of interest. Simulation is therefore not a direct or complete replacement for experiment. Rather, both simulations and experiments are essential adjuncts to the basic activity of developing the knowledge we need for the engineering design of Fusion reactors and Fusion reactor-based materials processing systems.

### III. Why A Special Purpose Machine?

In recent experiments, Culler-Harrison, Inc. found their inexpensive ($200,000) vector processor to be about 50 times more cost effective than a CDC-7600 (about $8,000,000) on the program kernels involved in plasma simulation[5]. Possible economies of specialization as high as 500 to 1 were observed by Cox [6]. Such economies are possible because specially tailored machines have only those function units which are needed, and they are balanced so as to get nearly 100 per cent utilization of all their hardware (as compared with a typical 6 per cent utilization of the function units of a CDC 6600 [7].

Because the plasma simulation problem is *very* well suited to parallel machine implementation (the vast majority of the computations involve only local information), enormous gains are possible here. As will be clear later in this paper, machines which can handle problems 25 to 100 times larger than presently possible, at speeds as great as 100 times faster per time step (net size-time gain of 2,500 to 10,000) may be feasible in the near term, somewhat smaller machines certainly are feasible in the near term. Additional factors of 50 to 500 are available within a few years with the development of special components and packaging. (Note: these stupendous gains are *size* gains, not cost-effectiveness gains).

Anticipated developments, like laser memories and magnetic bubble memories will enable even further advances. All advanced research should be heavily funded to enable us to have machines of the scale we will need in a fusion-based economy. We note in particular the possible exploitation of the Josephson effect switch recently demonstrated in the laboratory by IBM researchers. It is about 100 times faster than the present silicon transistor switch which has been used in the last several generations of computers[8].

### IV. Is A Mammoth Machine Really Feasible?

Given the industry's recent experience with the Illiac IV and the CDC Star, both of which have gone way over budget and are very late in being completed, it is reasonable to doubt that it is practical to build extremely large scale computers. This problem of massive cost over-runs is also endemic in the other half of the computer field, software. OS, the operating system for the 360 series, cost IBM much more than they had anticipated. TSS, the time share system for IBM's 360/67, never worked satisfactorally. Multics at MIT was a great disappointment[9].

For the problems not traceable to simple mismanagement, like not having enough inhouse expertise to evaluate contractors' claims, these failures can be traced not to scale per se, but rather to complexity. It is certainly possible to make the kinds of machines we will discuss below. The key is to respect the very great difficulty which complexity can cause, and therefore avoid significant amounts of it at all costs (including factors of two in performance). We would specify three definite rules for our designers:

1) Keep it simple.
2) Do not push the state of the art, or the ratings of the components.
3) Design it so it is easy to debug both initially and while it is running.

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* This the commonly accepted belief in the field, which I was taught.Recent evidence I have seen indicates that this may be untrue for the energies and densities involved in laser fusion.

(5) Dick Levey of Culler-Harrison, 150-A Aero Camino, Goleta, Calif. (Los Angeles), personal communication, June 1974.

(6) "Economy of Scale and Specialization in Large Computing Systems", Jerome R. Cox, Jr., Monograph 93, Biomedical Computing Laboratory, Washington University School of Medicine, St. Louis, Mo., 1968

(7) Michael J. Flynn, in a talk given at the Illiac Project at Ames Laboratory in California in the summer of 1972. This assertion was reaffirmed by Dr. Flynn when a member of the audience objected that it sounded unreasonably low and therefore unlikely. Also see, "Some Computer Organizations and Their Effectiveness", Hopkins Computer Research Reports No.12 (NYO-4208-12), The Johns Hopkins Univeristy, by Flynn.

(8) p.30, Modern Data, November 1973 (IBM's advertisement "DP Dialog")

(9) p. 42, Softward Engineering Techniques, Report on a Conference Sponsered by the NATO SCIENCE COMMITTEE, Rome, Italy, October 1969. Chairman: P.Ercoli, Editors: J.M. Buxton and B. randell, available from Scientific Affairs Division, NATO, Brussels 39, Belgium.

This last point needs some expansion. There are reasonably well developed techniques for exhaustively testing circuits of moderate complexity to detect any *single* failures[10]. A machine of the scale we contemplate needs to have diagnostic circuity for periodically automatically performing such checks. This is possible only if the problems of doing this are faced from the very first in the design—it can not be grafted on afterwards. Component reliability will probably be the ultimate limit to practical machine size, and the needs of fault diagnosis the primary things which require the development of special integrated circuits.

Resistance to and resiliance from failures is the single most important element in any design of this sort. When a failure occurs, the system should be able to recover from errors introduced by the failure before it was detected, and reconfigure itself so as to continue processing the problem as fast as it can, given the hardware that is still operational ("graceful degradation"). Needless to say, the system must be designed so that no single failure, and no likely multiple failure, can take the whole thing down (including failures in the power system and air conditioning system).

Another particular design criterion that bears mentioning is that the main busses in the system should be designed so that units can be unplugged from them or plugged into them while the machine is operating, without disturbing its operation.

## V. Who Should Build It?

The remaining question is who should build it. The job is specialization of hardware. This means the system must be designed from the top (the problems that run on it) down, to a much greater extent than is usual with machines. Hence, the people who are to use it must have the primary responsibility for its design and construction. This requires groups, and people, with both machine design and Plasma Simulation competence * . These people should both design their new computer and investigate new simulation algorithms and techniques which can be implemented in massive, parallel machines more easily than present techniques. (In computer work, experience has shown that the *biggest* efficiency gains always accrue from developing a better algorithm rather than from improving the efficiency of the implementation of a given algorithm.)

The A.E.C. now maintains (inhouse) groups of engineers and technicians for building large, special purpose experimental equipment. The sort of computer development proposed must clearly be handled in the same way. One coordinated organization whose primary responsibility is CTR development should be in charge of the whole effort, from use, through construction and design, to the funding and coordination of basic research in universities and elsewhere. (The effort may even need to extend into the fabrication of basic components. Machines of the scale we propose for immediate construction could consume, for instance, as much as a month's production of the country's largest semiconductor memory manufacturer. [11]

## VI. Plasma Simulation in General

Plasma simulation can be roughly broken into two classes, fluid and particle. In fluid simulation a set of fluid-like equations is set up, and assumed to describe the plasma behavior. The computer is them used to sovle them in some appropriate approximation, using standard, well developed, numerical hydrodynamic techniques. These techniques have the property, by and large, that the steps involved in the computation are very regular, and identical from one pass to the next. Therefore this is the easiest kind of simulation for which to make large, special purpose machines. Further, present super computers, like the CDC Star, the Illiac IV, and the Texas Instruments pipeline machine are all relatively well suited to this kind of problem.

Particle models attempt to simulate a plasma by following the motion of a large number of charged particles under the influence of their self-consistent electric and magnetic interactions. Such models most nearly emulate a plasma, and are hence most basic. However, they are limited in the size of plasma they can simulate because of the limitation of the number of particles which can be handled, in present and foreseeable machines. Therefore, particle codes are used for studying the microscopic behavior of plasmas, and fluid codes their macroscopic behavior, with particle codes often supplying the transport coefficients and such for the fluid codes. The computation steps required for a particle simulation are far less regular than those required for fluid simulations, because the elementary units of the computation, the particles, are moving about somewhat randomly.

Typical vector and array processors (like the present super computers), do not handle this variation in the

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(10) See for instance, "Fault Diagnosis of Digital Diagnosis of Digital Systems" by Herbert Y. Chang, Eric G. Manning, and Gernot Metze, Wiley-Interscience, 1974, and the card testing system of the Illiac IV project. Note: the Illiac IV is a good example of how NOT to deal with the testing problem — insufficient (or no) thought was given to these problems either in its initial conceptual design or its final detailed logic design.

* Some such people already exist and the interdisciplinary training required to make more is not exceptionally difficult. Machine design is very much like programming, and for those parts that are not like programming, physics is an excellent background. Similarly, going the other way, in the author's experience, the Plasma Physics concepts essential to simulation are not so foreign to good computer systems people's thinking as to pose a serious problem, and Electrical Engineers who design computer hardware generally have a good background in basic Physics.

*(11) a billion bits per month of 1103's by Intel Corp, according to p. 25, Computer Decisions, June 1974.

particle case gracefully. There is therefore more to be gained (over present methods) by making a special machine for particle simulation than there is to be gained by making one for fluid simulation. Additionally, the design problem is a bit more involved. For these two reasons, and because the author has coded a particle simulation but not a fluid simulation, this article will concentrate on machine design issues for particle simulations. However, from what the author knows about fluid simulation, the architecture presented later is also fairly well suited to it, for simple fluid simulations at least.

## VII. The Simulation Facility as a Whole

In this paper we will speak in detail only about the simulation itself. This is only one of four distinct parts in the whole job, each of which could be done on separate machines. These four parts are:

1) The simulation itself.
2) Monitoring the simulation, taking data.
3) Analyzing the data from the computational experiment, like drawing graphs (traditional experimental data reduction techniques are applicable, and necessary, here).
4) The human interface, for program preparation, for dynamic interaction with a simulation, and for what-ever other clerical support the computer can provide (viz. document preparation for report writing, and symbol manipulation for large, complex symbolic calculations done by Plasma theorists.).

The first two parts here are inherently highly parallel. We could envision two highly parallel machines intertwined so that one runs the simulation while the other watches it. Alternately, we could have only one such machine, and time share the hardware between the simulation and the data taking. The appropriate blending of these two concepts is an issue that must be investigated in detail.

We certainly want to have separate hardware for the data reduction and the human interface. The author doubts that there is much to be gained by making a special purpose machine for data reduction—the computations are neither massive nor regular enough. Optimal hardware (and software) for human interaction is a very deep problem, whose solution is applicable to many fields. This problem is the author's present primary research. Discussion of it past the comments immediately above is beyond the scope of this paper.

## VIII. Particle Simulation

A particle simulation is basically very simple. It divides roughly into two parts: updating particles and updating fields. We have a given configuration of particles. We want to know how this configuration changes through time. Unlike the case with simple systems, like the orbit of a satellite, we are not able to directly compute (predict) the configuration for all future times. We are only able to directly compute it for a very short time into the future. We get longer times by repeatedly computing the change in configuration which would occur over a short time, and adding these changes together. Each of these successive computations is called a time-step.

Now, more precisely: we begin with a large number of particles (in a typical present day two dimensional simulation we would have about 500,000), with given positions and velocities. From these positions and velocities we compute the electric and magnetic fields produced by the particles. We add to this whatever external fields are applied to the plasma. The resulting field determines the *changes* in the *velocities* of the particles over the short time of the time-step. The (average) velocity of each particle during the time-step determines its *change* in *position*. The new velocities and positions, in turn then determine a new set of fields, from which we compute the next time-step's velocity and position (i.e., configuration) change, etc. We do not need to go into the exact method of updating the positions and velocities (for instance, determining the average velocity over the time interval) here. We do, however, need to say a little more about the field calculation.

In principle, the job of determining the forces acting on a particular particle involves looking at all other particles relative to the given particle. Using each particle's position and velocity relative to the given particle, we must compute how each particle's electric and magnetic fields affect the given particle, and add together all these effects. Doing it exactly this way would be excessively expensive, and is unnecessary. Instead we can compute global electric and magnetic fields, approximating the continuous fields throughout the portion of the plasma being simulated by values at a grid of discrete points. In typical present day two-dimensional simulations this grid is 128 points on a side, and requires about a dozen numbers at each grid point in order to represent the fields and keep track of other necessary information. The actual force on a particle is then computed by interpolating among the nearest grid points. This grid is a fixed reference frame, and it "wraps around." When a particle goes off one side, it is brought back on the other side. This means, in effect, that we are looking at a one period size piece of a large, periodic plasma.

The techniques for computing these force fields on present machines are quite efficient and require only about 10 per cent of the time in present simulations. However, these techniques are dependent on the global information availability accruing from having all of the field information in main memory at once, and having only a small number of processors accessing it.

By virtue of having the fields, the particle update half of the computation involves strictly local information and can therefore be done very efficiently on a simple, many-processor highly parallel machine. The field computation, however, inherently requires more global information flows.It can therefore not be done *efficiently* on such a machine. The best way to do it on such a machine would probably be to use the older differencing techniques, which require less global information flows, (but which are markedly less efficient than present day Fast Fourrier Transform techniques).

Given that our objective is to obtain economies of specialization, the proper solution to this problem would appear to be the construction of two machines. One does particle updates and the other does field updates. To obtain a high percentage machine utilization this machine pair would be designed to run two simulations simultaneously, performing the field update on one while performing the particle update on the other.

This paper will concentrate on the particle update half of this machine. This paper's purpose is, after all, not to present a complete, debugged machine design, but rather to present the option of constructing special purpose machines, pointing out the primary issues involved in such an endeavor and illustrating the sort of thing that might be done.

At first glance, the principal issue in the particle update would appear to be the actual numerical operations. Exactly what operations are required in the particle update depends on exactly what the simulation model happens to be. A relatively involved computation can be required. One of the codes currently in use at Livermore requires 27 microseconds to update a particle, using the CDC 7600. This code includes both magnetic effects and an explicit relativistic correction [12].

However, inspite of this complexity, the real problem in building a simulation machine is not in performing these operations. The real problem is gathering the operands together and delivering them to the function units. Even with the explicit square root, the program mentioned immediately above is input-output bound (the particle information is stored on the disk). A microprogramable function unit capable of doing fixed point multiply-add pairs in less than 200 nanosecods per pair (floating point is unnecessary), and capable of storing the few program steps required in the particle update kernel can be built quite cheaply out of off-the-shelf components these days[13]. It could fit on a few medium-sized printed circuit boards and cost under a thousand dollars. Hence a thousand of them, giving a net multiply-add speed of 200 picoseconds for the machine as a whole, would cost less than a million dollars. (A CDC 7600 costs about 8 million dollars.) The biggest expense, and the problem that puts the strongest constraints on the machine architecture is that of transferring the operands to working storage and, hardest of all, locating and fetching the field information applicable to a given particle, once you have the particle in working storage. However, it turns out that there are acceptedly simple ways of solving this problem.

## IX. Conceptual Design of The Particle Update Half of a Machine

The sort of considerations required to design a machine on the level we will discuss it here are very much like those required to design a highly optimized program. In general, machine design and programming are very similar activities. Except, the functional design of a machine is just the tip of an iceberg. Designing for rapid and effective fault detection and repair, and for graceful degredation are the hardest problems and are where the poorest jobs have been done in the past. We will not discuss these issues in any great this p they are sufficiently disjoint from functional design to be reasonably ignored in the first approximation. However, it is important to note that these are by far the hardest problems in mammoth machine design. We need to aim for nothing less than being able to detect marginal conditions before they result in failure. (Detecting hard logic failures very soon after they occur is not enough.) This will require a much more thorough understanding of the physics of marginal and failing devices than we now have, and designing monitoring circuitry, of an analogue character, into the basic circuits themselves.

This work will be expensive and time-consuming, but it is essential to a future computer and fusion-based economy. Its importance and difficulty does not mean it is impractical to build large machines right now. On the contrary. It means this research must be started immediately and that the first two or three generations of mammoth Plasma Simulation machines will be as much fault detection and correction research tools as they are Plasma Physics research tools. It also means, of course, that the engineers responsible for the detailed design of these machines can not be "run of the mill" computer design engineers. They must be people with some competence in fault diagnosis[*].

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(12) Chris Barnes, Stanford University, personal communication, July 1974. Incidentally, Dr. Barnes related having arrived at substantially the same machine architecture as presented here, about two years ago, dropping his investigation because there was manifestly no interest in such a venture.

(13) The TTL Data Book, by the Engineering Staff of Texas Instruments Inc. Components Group, First Edition 1973.

(*) You will note that the combination of section V and this comment specifies a project management made up on one hand of people who will be using the machine and who are therefore concerned with its reliability and usability, and on the other hand of people who know how to provide this necessary reliability by building detailed fault detection systems—and who know such systems are necessary. This is very important. Further, global considerations of this sort are far

The following discussion deals with the conceptual design of a machine, as distinct from its detailed logical design. Determining things like exactly how many busses, exactly how many processors, and exactly how much memory per processor requires careful simulation of the machine.

For our conceptual design considerations, the first issue is the scale of problem we want to tackle. At present, the most common large simulations are two dimensional, with grid sizes of 128x128 and about 500,000 particles, and they run at about 10 seconds a time step on the CDC 7600. This is 360 time steps per hour: about three hours for 1000 time steps, or 30 hours for 10,000 time steps (30 to 50 hours is as long as it is practical to run such a simulation on present systems[14]).

Several important classes of problems could be tackled if two dimensional problems as large as 1000x1000, requiring 30,000,000 particles could be run, for as long as 100,000 to 1,000,000 time steps[15]. To do 1,000,000 time-steps in 30 to 50 hours requires a time-step computation time of .1 to .2 seconds. This is a net time per particle-time-step of 3 to 6 nanoseconds. A particle in this kind of simulation requires between 100 and 200 bits, a grid point between 300 and 400 bits[16]. This means we need 3 to 6 billion bits of storage for the particles and 300 to 400 million bits for the grid points.

Three dimensional problems, which are generally not done at present, require grids of 100x100x100 with 100,000,000 particles, and runs up to 10,000 time steps[17]. A 30 hour 10,000 step run requires a time-step time of about 10 seconds and hence a time per particle-time-step of 100 nanoseconds. Significantly more storage is required here because of the additional dimension, 25 to 30 billion bits for the particles and 400 to 600 million bits for the grid points.

These are the orders of magnitude of size and speed we want to shoot for. 1 billion bits of shift register memory at .1 cents a bit is only 3 million dollars. 30 billion bits fit on 30 IBM 3330 disks. Hence, these numbers are not orders of magnitude (or even an order of magnitude) beyond what is feasible with off-the-shelf equipment and packaging!

The sheer size of the number of particles requires that they be stored on some kind of "rotating mass storage." The grid points do not, strictly, have to also be stored there, the number of bits required for them is just within what is economically feasible for random access memory these days. However, a most significant fact is that the particle update computation can be organized so there is no advantage to having them in random access storage. If we are able to arrange the field update similarly, the new technologies being developed in the rotating memory field could make a very big difference in the scale of machine it is practical to build.

We noted above that the bottleneck in a particle update is not the numerical computations *in* the function units, but rather the task of getting the right operands *to* the function units. There are two problems here. The first is getting the information into the main memory from the disk. This is expensive but not really difficult (it is not complicated). State of the art disk transfer speeds are about 5 million bits per second per track. In the large two dimensional simulation above, if we use only about 120 bits/particles, 3.6 billion bits would have to pass through the machine each time-step (.1 seconds). This is a net data rate in and out of the machine of 36 billion bits per second, or about 8000 tracks reading and writing simultaneously. This is a lot, but it is not totally out of the question—8,000 read-write units at 500 to 1000 dollars each cost 4 to 8 million dollars. This is the order of magnitude we expect. It looks like the single largest expense.

The other problem is bringing the right grid point information together with the particle information. This introduces some significant complication. If the particles did not move around, this would be no problem. The particle information could be arranged in the same order as the grid point information, and as each section of the grid was brought into core, the particles in that section would be brought in. The usual way this problem is dealt with in present simulations is to keep all of the grid in core all of the time. The necessary reference to *an arbitrary place in the grid for each particle then is facilitated by the random access nature of the memory. The throughput of this technique is limited by the speed of the random access memory, and it is therefore impractical, as we show below.*

Memory of the speed we could afford in this quantity has a cycle time of about 500 nanoseconds. At a minimum of 5 references per particle (4 for the enclosing grid points for obtaining the force information from the grid, and 1 for feeding configuration information back into the grid), this requires 2500 nanoseconds per particle, which means the memory would have to have 833 ports to handle 30 million particles in .1 seconds. This is not practical, and fortunately it is totally unnecessary, because, as we show below, it *is* practical to

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more significant for the success or failure of this sort of endeavor than any particular technical design point. Additional such issues are level of pay (which means relative quality of people), level of clerical and technical support, responsiveness of the computer systems supporting the design effort, and the human factors of the physical environment. These sound like platitudes. This is because everybody knows they are important, but they are **such difficult problems** that they are usually ignored (in whole or in part).

(14) Bill Kruer, Lawrence Livermore Laboratory, personal communication, July 1974.

(15) ibid.

(16) Ken Estabrook, Lawrence Laboratory, personal communication, July 1974

(17) J. Dawson, UCLA Physics Department, personal communication, 1974

keep the particles approximately sorted on the disk, so you can pull in all (and only) the particles that are in the vicinity of a particular set of grid points. (Of critical importance here is the fact that the average particle travels a distance equal to the spacing between grid points in each time step[*]).

The way to understand the process of keeping the particles sorted is to focus on the grid rather than the particles. The computation is organized as a job of updating all the particles in a given grid square rather than updating a particular particle. For simplicity, for the next several paragraphs we will ignore the problems of:

1) particles that move more than 1 square, and
2) major density variations from one part of the plasma to another.

The input to this updating process is (in the 2-d case) from 9 sources—the particles that did not move out of the given square during the last time step, and the particles that moved into the given square from each of the 8 adjacent squares during the last time step. The output from this process is similarly to 9 destinations rather than just 1. (In the 3-d case this number is 27 rather than 9.)

One way the sorting could be done can be seen by considering the case of having 1000 processors processing in a 1000x1000 grid. We could process a swath 1 square wide across the entire grid. We are able to arrange to get all of the particles that move into a particular square during a time step into one buffer as the computation moves past that square. Hence, there need be only 4 active buffers per processor. One is the buffer containing the particles in that processor's square at the beginning of the time step (input buffer). The other 3 are output buffers, they are for the square in front of the present square, the present square, and the square behind the present square.

The memory must be multiply ported so each processor has access to both its 4 buffers, and to the 3 output buffers at both of its adjacent neighbors (note: the bottom row of squares is adjacent to the top row). The processor works through its input buffer, thus:

1) Pick up particle.
2) Compute its new velocity.
3) Compute its new position.
4) Put it into the appropriate output buffer.

To do it exactly this way the output circuitry would actually have to be one circuit per processor because we neither want two processors to simultaneously write into the same word of an output buffer not one processor to hang waiting for another to finish writing into the buffer. A simpler way to solve this problem (remember the need for simplicity!) would be to have more memory (simplicity is *always* more expensive in component count for the same level of performance), giving each processor a complete set of output buffers, and then have another set of much simpler processors which merge the buffers after the processors have moved on.

Now what about particles that move more than 1 square? Motion to the side is no problem, as all these buffers are in core. For motion out of the region presently in core, we have to keep a large enough region in core that the number of particles that show up needing to go into buffers that are not in core is small enough that they can be kept in core (or some other relatively fast place) until the input processor can merge them into the squares they belong in, as the squares are brought into main memory the next time around. This is the general model for handling these sorts of randomness problems. Make a general procedure, one involving only local information flows, that handles enough of the cases that special, more global information transfer hardware can handle the few that are left.

The random access memory system for this hypothetical 1000 processor machine, for the 2-d case, would be of the order of 8 million words (about 36 bits wide), organized into 1000 modules. Each module would have 16 ports: 5 for the sorting processors, so they can reach two processors to either side, about three for the rotating store input-output processors (so each rotating store module is not tied down to one location), two for the function unit (one for input, one for output), and about 6 for more global busses for handling exceptionally fast particles, data gathering, intitialization and what not. (Note: additional data paths may be needed by the field calculation—and additional data paths surely are needed to enable the rapid, electronic substitution of a backup processor/memory unit when one fails during a computation.) Each of the 1000 modules would be further modularized so each of the three processors can be running (at full speed) at the same time. Each port must contain one or two bit error-correcting hardware, as semiconductor memory is a somewhat less reliable than core memory, and we have so much of it that unless we are cautious, the probability of a significant error in a run will be too great.

The rotating store would similarly be organized with 1000 ports, and have a substantial error correcting capability. For error recovery, it presumably needs to be twice as large as indicated in our original comments about size above so as to be able to store a checkpoint configuration.

The basic bottleneck in this architecture actually turns out to be the effective throughput of the main memory, even with all of the multiple porting and interleaving we can do.

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(*) This is a constraint of the nature of the approximation technique which is this kind of Particle Simulation.

Now what about density variations? This is clearly a significant problem in a machine of this sort. As described, if the worst case density fluctuation was a factor of three, some processors would have three times as many particles to update as others, hence some processors would be idle two thirds of the time. Further, ion waves consisting of density fluctuations of a factor of three are not uncommon[18]. What we have here is a problem of allocating manpower. Consider a concrete hypothetical example of a large open top boat with many open top compartments. In each compartment there is a man with a bailing bucket. The boat is both leaky and there are waves splashing over the side from time to time, so all compartments need to be bailed, but from time to time any of the compartments might become exceptionally flooded. The process of bailing water out of a compartment is a good analogue of the process of updating particles in a given grid square. In the boat case the manpower allocation problem is simply one of being able to have two or more men bailing one compartment, while elsewhere in the boat one man bails two or more compartments (jumping back and forth).

In computerese, the process of updating the particles in a given square is a task. Having one processor handling more than one square is then the well-known technique of multi-tasking (also called multi-programming). Additionally, these are very special tasks in that they are made up of a large number of *independent* subtasks (each particle update). It is therefore possible to do the inverse of multi-tasking, and have several processors working on one task, that is, several processors updating the particles in one square.

So the solution to the density variation problem is to break the rigid, one processor per square structure implied above originally: instead you have one *software process* per square (possibly assisted by a little bit of hardware), with the *hardware processors* assigned flexibly among adjacent *software processes.* Probably the biggest impact this has on the machine is to extend the range it is necessary for the local busses to span. It is difficult to tell without some detailed simulation of the machine.

## X. A Caveat

This paper was written over a very short time. It therefore may have several significant errors in it. Its objective is not to be air tight, but rather to make the feasibility of building large special purpose machines sufficiently plausible to warrent further expenditure, and to seriously raise the question as to why this has not been pursued before by the powers that be.

The author has purposely gone to the limit of feasibility for present packaging techniques and reliability in suggesting a 1000 to 10,000 processor machine with 8 or more thousand words of random access memory and 1,000,000 bits or so of rotating store per processor. The sheer physical size of such a machine, whereas physically possible, offends one's sense of engineering esthetics. Present standard packaging techniques were not intended for things this big. But then, there do exist more compact packaging techniques which are reasonably well developed, and special purpose integrated circuits are not all that hard or expensive to make, and many things that can be done about the reliability problem are well known.

The point is that this sort of special machine design has become eminently practical in the last few years and it therefore must be seriously considered in any serious fusion research program. Whereas machines of as large a scale as a 1000x1000 2-d machine with a time-step time of .1 seconds might not be the right thing to do immediately, something like the following certainly would: for rotating store use 10 to 30 IBM 3330 like disk systems (about 1 billion bits per spindle, 10 platters per spindle), provide read-write electronics for each head so as to have 200 to 600 data streams. The data transfer speed of the 3330 is 6.4 million bits per second. Between 50 and 500 simple processors (one fixed point multiplier and one fixed point adder, and one shifting/masking unit for the exceptional cases when floating point is needed) built out of off-the-shelf components, such as the Texas Instruments (TI) SN74284 and 285 multiplier chip set (120 ns for a 40 bit multiply), and the TI SN74S181 and 182 arithmetic logic unit set (28 ns for a 40 bit add[19]), should be able to handle this data rate. Work on such a machine, and on fault diagnosis research and on other research basic to mammoth simulation machine design and construction should receive immediate, substantial funding.

## XI. Present AEC Activities in Computing

The A.E.C. at present has an effort (woefully small) in special purpose machine utilization, centered around the Culler-Harrison signal processing system (vector processor) mentioned above in Section III. To have an effort at all is commendable. To have such a small one is suspicious.

In the last year the A.E.C. has (at long last) officially recognized simulation as an important part of the fusion program, and begun a project to construct a special computer center for this work. This effort is commendable, and the design as presented in the specifications (LLL-SE-72-2, -3, -4) is excellent, given (again) the framework within which those who designed it constrained themselves to work. Viewing this computer center design from within the framework of this

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(18) Bill Kruer, op. cit.

(19) The TTL Data Book, op. cit.

paper, we see the proposed system as an adequate implementation of parts three and four of a simulation facility as defined above in Section VII (with the exception of the slow data transfer speed to the user CRT terminals). I am told that the people involved in the project are aware that their main computer (as specified in the above name specification) is not large enough for even the present simulation effort, and are considering what steps should be taken to increase the center's power. The decision on this matter should include the immediate vigorous pursuit of specially configured highly parallel machines, as discussed in this paper!

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# The Conceptual Design of A Tokamak Fusion Power Reactor, UWMAK-I

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## I. INTRODUCTION

Scientists have recently become more and more optimistic about achieving a positive power balance from controlled thermonuclear reactions. However, such a momentous achievement does not automatically mean that the road to economic power generation will be assured. In order to aid in the assessment of the technological problems associated with fusion power, a group of scientists and engineers at the University of Wisconsin initiated a design study of a large electrical power generating station based on the Tokamak concept and fueled with deuterium and tritium. The goal has been to conduct a self consistent study from the standpoint of plasma physics, neutronics, materials, magnets, power cycle, environment, resources and cost. In this paper, we summarize the design features of a 5000 $MW_{th}$ D-T Tokamak conceptual power reactor called UWMAK-I (University of Wisconsin Tokamak). A subsequent paper in this volume will emphasize the major conclusions, implications and recommendations of this work. A much more detailed description of this study is described in a University of Wisconsin report (1).

## II. REACTOR DESCRIPTION

### A. General Features

The UWMAK-I reactor has been designed with the philosophy that whenever possible, decisions should be made on the basis of a reasonable extension of present-day technology. Such a constraint has produced a rather conservative design which may appear less efficient and perhaps more expensive than more advanced concepts (2-4). The major design features of UWMAK-I are listed in Table 1.

Table 1

UWMAK-I Operating Characteristics

| | |
|---|---|
| POWER | 5000 $MW_t$<br>1500 $MW_e$ |
| FUEL CYCLE | (D-T), Li |
| DIMENSIONS | R=13m, a=5m |
| DIVERTOR | POLOIDAL DOUBLE-NULL |
| COOLANT | LITHIUM |
| STRUCTURAL MATERIAL | 316 STAINLESS STEEL |
| NEUTRON WALL LOADING | 1.25 $MW/m^2$ |
| MAGNETIC FIELD | $B_t^o = 3.82$ T<br>$B_t^{max} = 8.66$ T |
| MAGNETS (SUPERCONDUCTING) | NbTi (CRYOGENICALLY STABILIZED WITH Cu) |
| POWER CYCLE | Li-Na-Steam |

The power level was limited to 5000 $MW_{th}$ even though the electrical generation costs in the Tokamak reactors may be somewhat cheaper at higher power levels. It was felt that when fusion reactors might be introduced into electrical networks (~the year 2000), units as large as 1500-2000 $MW_e$ would be acceptable.

The choice of a D-T fuel cycle (as opposed to a D-D of D-$He^3$) stems from the belief that we will achieve the D-T reaction first because of its lower ignition temperature and because it returns more energy per unit of energy invested. Such a decision has a significant impact on the technological problems that need to be faced (e.g. radiation damage, need for lithium, tritium handling, etc.).

The size of the reactor was dictated by optimizing the cost per unit power in a $\beta$-limited system. The costs were assumed to scale as the superconducting magnet costs. Subsequent work reveals that when all of the non-nuclear component costs are included, this may be a very conservative constraint tending to make the unit power costs somewhat high. When the 5000 $MW_{th}$ power level is coupled with a radiation damage limitation of 1.25 MW/m2 neutron wall loading, an optimum aspect ratio of 2.6 is indicated. This aspect ratio is best satisfied with a plasma radius of 5 meters and major radius of 13 meters.

The coolant, moderator, and breeding material has been chosen to be lithium (Li). Liquid metals have been shown to be efficient heat transfer fluids at a high temperature and not subject to radiation damage. It was originally thought that a major disadvantage of moving an electrically conducting fluid through high magnetic fields would be the high MHD pumping loss. However, by clever design, this pumping power requirement can be as little as 1-2% of the gross plant output which is actually less than required for gas cooling. The use of liquid metals also reduces the stresses in the reactor walls (e.g. lithium pressure of 400 psi vs. helium pressure of ~ 750 psi for helium gas cooling). Finally, the use of Li as a coolant also greatly improves the tritium breeding in a Tokamak reactor. One real disadvantage of Li is that when used with austenitic steels or nickel base alloys, lower operating temperatures are required because of excessive corrosion. (5) Nevertheless, the decision was made to use Li in UWMAK-I. Subsequent studies will investigate alternate coolants.

The structural material chosen for UWMAK-I is 316 stainless steel (SS). This choice is consistent with our design philosophy to use present day technology whenever possible. The steel industry has a long-established record of providing large quantities of high quality fabricated components. Recently the quality assurance procedures of the industry have been upgraded further to produce nuclear grade components for the LMFBR program. There is a wealth of thermal, mechanical, chemical, neutronic, physical and economic data on 316 SS both in liquid metal and irradiation environments. *No* such extensive data exists for refractory metals; nor is there an established industry for these metals at the present time or in the foreseeable future. The choice of a 316 SS-Li system appears to limit the operating temperature to $500^{0}$C because of corrosion, but if that were not the case, a maximum temperature of $650^{0}$C could not be exceeded because of excessive creep. Hence, our design philosophy has been to limit the 316 SS temperature to $<500^{0}$C at all points in the reactor. Such a decision means that the efficiency of the reactor will probably be limited to ~30%.

Consistent with a conservative design philosophy, a decision was made to use NbTi superconductors because of their ductility and ease of fabrication. Such a decision limits the maximum magnetic field in the superconductor to $<90$ kG at $4.2^{0}$K and to 40 kG on the axis of the plasma because of the geometry of the reactor. The magnets are cryogenically stabilized with copper in order to insure high reliability.

Finally, the power cycle consists of a lithium primary coolant which transfers its energy to a sodium secondary loop. The sodium in turn is coupled to a conventional steam turbine system.

Overall plant views of the reactor building are shown in Figures 1 and 2 while Figure 3 shows a cross section view of the reactor and its associated transformer and divertor coils. The fine points of these figures will become apparent in the subsequent discussion.

## B. Plasma Properties

The operating cycle of UWMAK-I is given in Table 2. The burn time of 5400 seconds (90 min.) compares with a total recharge time of 390 seconds (6.5 min.). This gives a duty factor of 93.3% for the operating cycle. However, the plant factor is closer to 80% when scheduled and unscheduled outages are included.

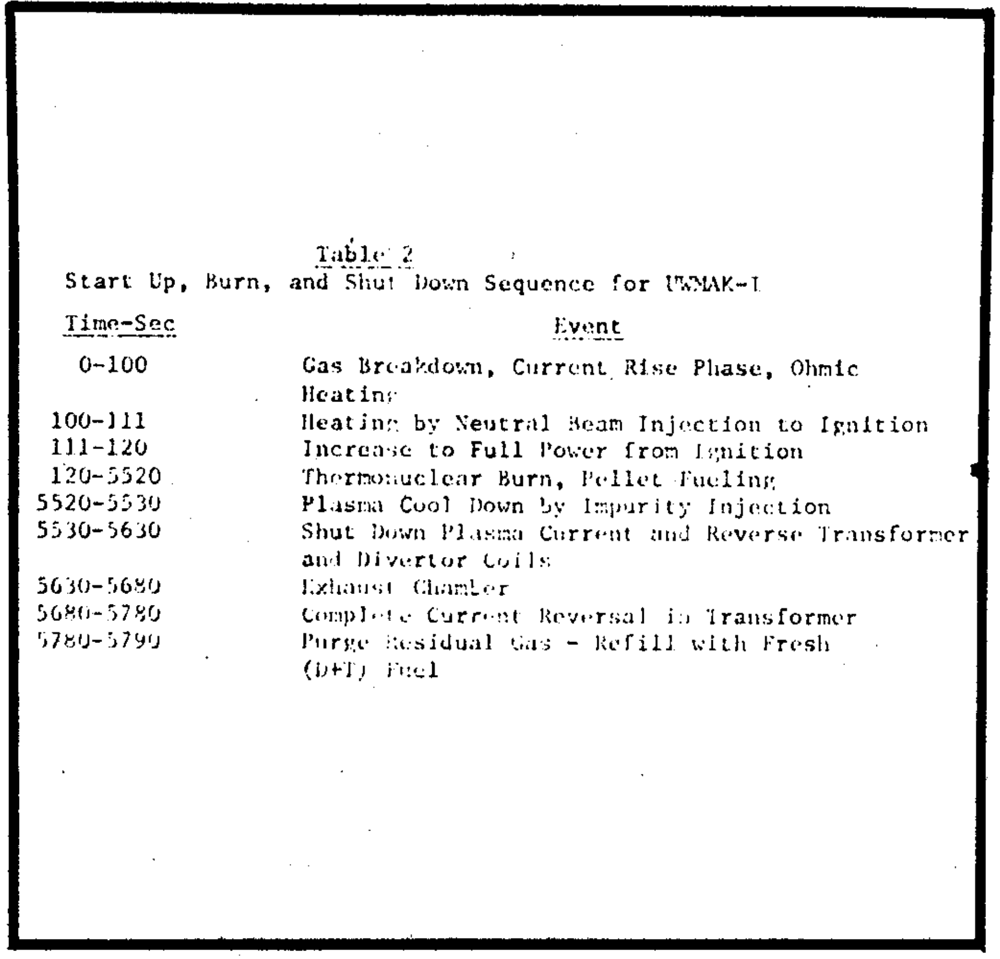


Table 2

Start Up, Burn, and Shut Down Sequence for UWMAK-I

| Time-Sec | Event |
|---|---|
| 0-100 | Gas Breakdown, Current Rise Phase, Ohmic Heating |
| 100-111 | Heating by Neutral Beam Injection to Ignition |
| 111-120 | Increase to Full Power from Ignition |
| 120-5520 | Thermonuclear Burn, Pellet Fueling |
| 5520-5530 | Plasma Cool Down by Impurity Injection |
| 5530-5630 | Shut Down Plasma Current and Reverse Transformer and Divertor Coils |
| 5630-5680 | Exhaust Chamber |
| 5680-5780 | Complete Current Reversal in Transformer |
| 5780-5790 | Purge Residual Gas - Refill with Fresh (D+T) Fuel |

Reactor startup makes use of an air-core transformer with superconducting windings (see Figure 3), a configuration most consistent with the small aspect ratio demands of the cost optimization. The transformer and divertor coil currents are programmed to rise with the plasma current, producing a time changing flux through the plane of the plasma. For UWMAK-I, the divertor actually provides 60% of the flux needed to energize the

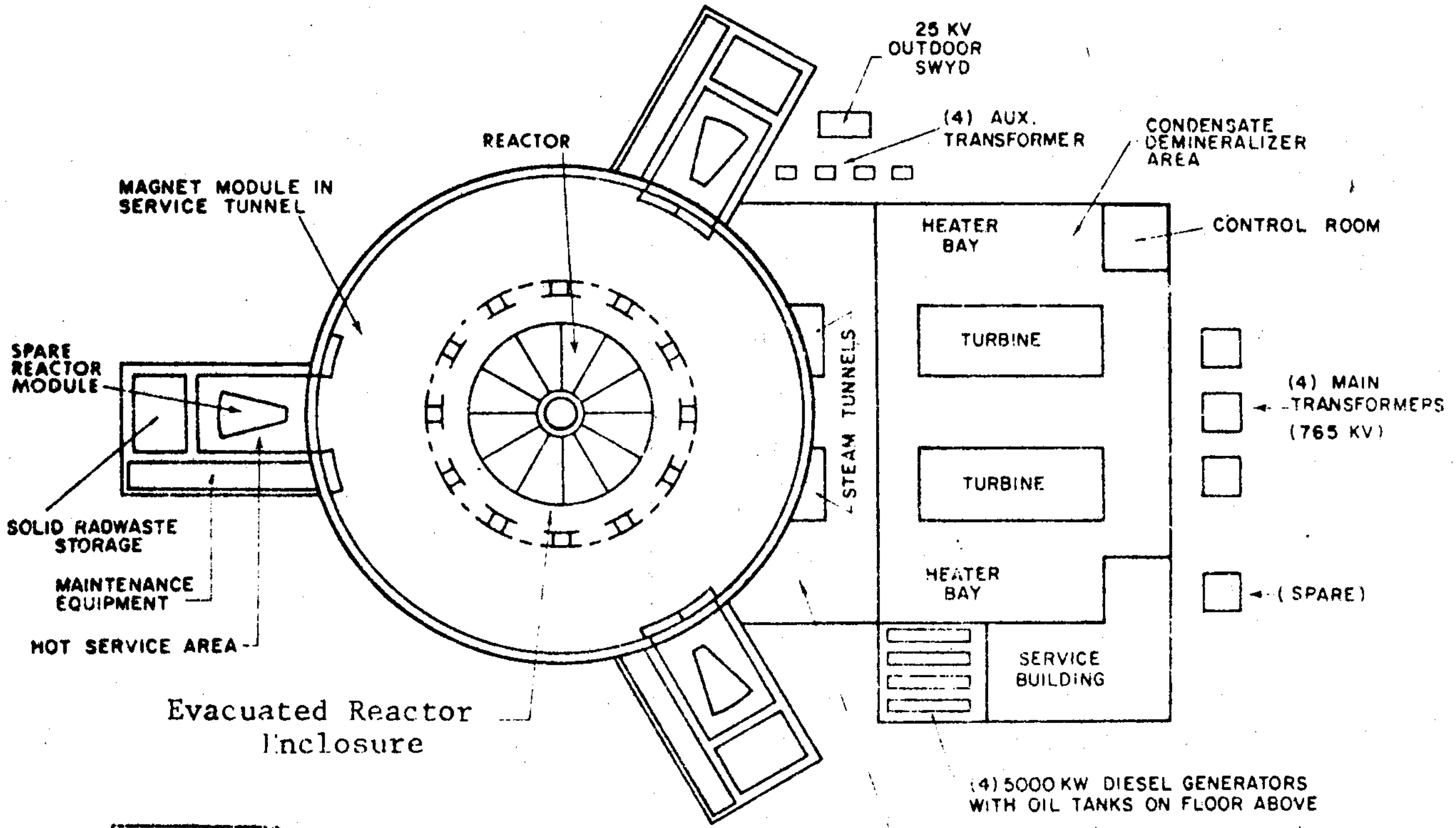


Figure 1

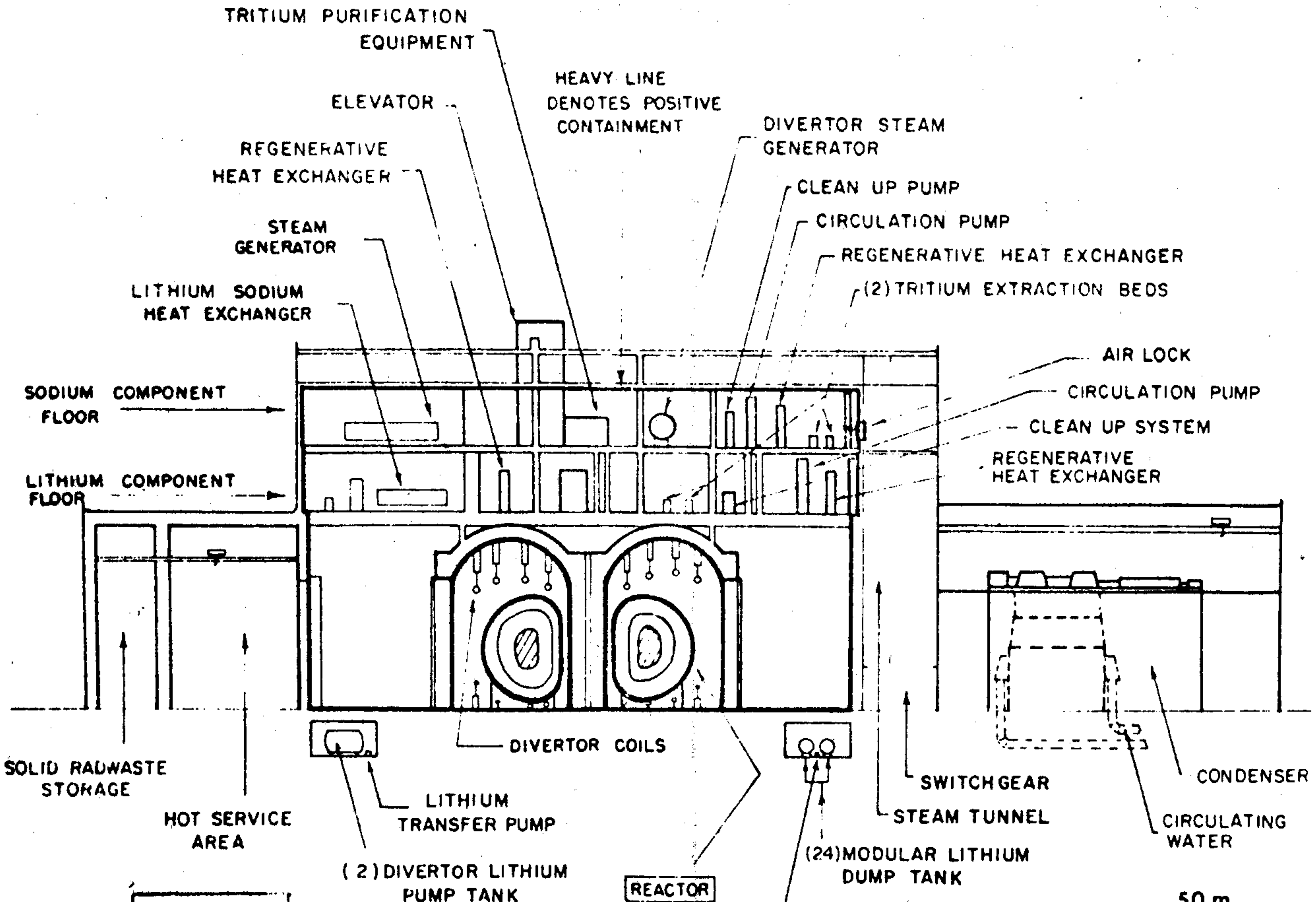


Figure 2

plasma current so that the transformer proper need provide only 40%. The current in the plasma rises in a controlled manner to its operating value of 20.7 Mamps in 100 seconds. A total of 430 volt-seconds are required to energize the plasma current. After the poloidal field of the plasma current soaks through the surrounding structure, the core flux is held constant if there is a bootstrap current (6). However, this has not been assumed in this work. Rather, the resistivity has been assumed to be anomalously high by a factor of 3.5 relative to the Spitzer resistivity. This implies an extra 330 volt-seconds for a 90 minute burn time and a total volt-second requirement of 760.

Plasma heating to ignition is via the use of neutral beams. Ohmic heating alone is insufficient. Neutral beams of 500 KeV injected tangent to the magnetic axis, penetrate the UWMAK-I plasma when a low density startup is used. The initial ion density on axis is 3 x $10^{13}/cm^3$. With tangential injection, all beam particles are on circulating orbits following ionization. The profile of power deposition per plasma particle is peaked on axis. The beams are turned on immediately after the plasma current has risen to its final value. Using 500 KeV beams and 15 MW of power, the plasma ignites in 11 seconds. Faster startups can be achieved by using more power but this is not advantageous in UWMAK-I. In the 500 KeV beam case, 99.5% of the beam is trapped in the plasma. Thus, neutral beam heating appears to be an effective way to ignite a large, power producing reactor such as UWMAK-I.

Once ignited, the plasma is assumed to rise in ~10 seconds to the operating conditions listed in Table 3. If the scaling is quasi-classical (that is, the diffusivity varies as $T^{-1/2}$ but contains an anomalous multiplicative coefficient relative to the classical value of the diffusivity,) then plasma operation under these conditions is thermally unstable and requires feedback control. The anomalous factor, S= 450, in Table 3 is relative to the neoclassical value of $D_{\perp}$ at the plasma conditions listed. The confinement time has been obtained from $\tau = a^2/4D_{\perp}$ .

Table 4

UWMAK-I Toroidal Magnet Characteristics

| | |
|---|---|
| Minimum Bore Diameter | 14.8 meters |
| Maximum Field at Superconductor | 8.66 T |
| Superconductor | NbTi |
| Stabilizer | Cu |
| Support Material | Stainless Steel |
| Maximum Stress in Steel | 4220 kgf/cm$^2$ (60,000 psi) at 4.2°K |
| Maximum Strain in Copper | 0.2% |
| Total Amps per Conductor | 10212 Amps |
| Conductors Per Disc | 60 |
| Discs per Magnet | 34 |
| Number of Magnets | 12 |
| Gross Current Density | 1318 Amps/cm$^2$ |

Table 3

Operating Plasma Parameters for UWMAK-I

$T_{ions}$ = 11.1 KeV
$T_{el}$ = 11.0 KeV
$\bar{n}_{D+T}$ = 0.8 x $10^{14}/cm^3$
$\bar{n}_{\alpha}$ = .0295 x $10^{14}/cm^3$
$\bar{\tau}_c$ = 14.2 sec
Confinement Spoiling Factor = 450
$Z_{eff}$ = 3.5
$f_b$ = 7.2%
$n\tau_c$ = 11.35 x $10^{14}$sec-cm$^{-3}$
$\bar{\beta}_{\theta}$ = 1.07
$\bar{\beta}_{\phi}$ = .052

q(a) = 1.75
a = 5m
R = 13m
$r_w$ = 5.5m
A = 2.6
$B^o_{\phi}$ = 38.2 kG
$B_{\theta}(a)$ = 8.4 kG
Plasma Vol. = 6400 m$^3$
Chamber Vol. = 7750 m$^3$ (nominal)
Wall Area = 2830 m$^2$ (nominal)
$I_{\phi}$ = 20.7 x $10^6$ Amps.

The UWMAK-I design imposes a conservative limit on $\bar{\beta}_{\theta}$ of one. Present experiments achieve a $\bar{\beta}_{\theta}$ of about one-half and the recent, low-aspect ratio, MHD equilibrium studies of Callen and Dory (8) give, as a best case, $\bar{\beta}_{\Phi} \sim$ 0.1 and $\bar{\beta}_{\theta} \sim 2$. For UWMAK-I, we have chosen values intermediate between these and somewhat arbitrarily used $\bar{\beta}_{\theta} \sim$ 1 and $\bar{\beta}_{\Phi} \sim$ 0.05.

To achieve favorable operating conditions with quasi-classical scaling, energy losses from the plasma have to be increased via the addition of 0.95% argon impurity atoms. Further, as noted above, the average confinement time of ~14 sec is 2 orders of magnitude shorter than is predicted by neoclassical theory. Such reduction in confinement time, relative to neoclassical scaling, is required to both achieve a favorable power balance at $T_i$ = 11.1 KeV, as listed, and to remove spent fuel ($\alpha$-particles) so that a respectable D+T ion density can be maintained. For these operating conditions, the plasma is a low $\bar{\beta}$ ($\bar{\beta}_{\Phi}$ =0.052, $\bar{\beta}_{\theta}$ =1.07), low field ($\beta^{o}_{\Phi}$ = 3.82 Tesla) reactor producing 5000 $MW_T$, based on a total of 20 MeV per fusion event. If the bootstrap current exists, the plasma is assumed to operate at these conditions until impurity buildup from wall erosion (because the divertor is not 100% efficient) causes excessive losses and requires shutdown and purging. Otherwise, the burn time is determined by available core flux to be 90 minutes.

The plasma characterized in Table 3 is assumed to be fueled during operation by injecting solid (D+T) pellets to make up for losses due to fusion and diffusion. The use of neutral beams for this purpose is highly questionable. Beam penetration is more difficult at the average operating density of 0.8 x $10^{14}$/cm3 and further, the leakage rate of 3.6x10 22 (D+T) ions/sec means that ~3000 MWe of power are required when 500 KeV beams are used. Higher energy beams implying even larger power requirements are clearly not economical. Fueling is therefore assumed to be via pellet injection, using 20 micron radius pellets injected at the rate of 20 x 106 pellets per second. The former requirements are closer to current technology, assuming the plasma can withstand pellet injection in the first place.

At the end of the burn cycle, the plasma is quenched by injecting impurities for 10 seconds. After the power level is lowered, the currents are reversed in the transformer and divertor coils 100 seconds. The chamber will then be purged to remove unburnt fuel, helium "ash," and impurities over a 50 second period. Another 100 seconds is ued to complete the current reversal in the transformer. A final 10 seconds is used to purge any residual impurities that have been collected during the current reversal phase. Refueling with fresh D+T will also be accomplished near the end of this 10 seconds.

UWMAK-I utilizes a double neutral point poloidal divertor generated by superconducting coils outside the toroidal D-magnets. (Fig. 3) The coil locations, currents, and separatrix (plasma boundary) are shown in more detail in Fig.4. The particles diffusing from the plasma are collected by a flowing lithium surface with a trapping efficiency of 96%. The lithium flow down the face of a stainless steel plate, under gravity alone, and the flow rate of 10 kg/sec is such that no additional cooling of the backing plate is required. More details of this system can be found in Reference 2.

## C. Magnet Design

The main toroidal field magnets are superconducting using NbTi cryogenically stabilized with copper. We have concluded that such fully stabilized magnets are the most feasible and that there is no need for unstabilized magnets. The NbTi filaments are contained in a large 2 cm x 2 cm conductor and the conductor is mechanically mounted, not loosely wound. Winding with wire or tape is very difficult for such large bore magnets. A list of the magnet characteristics are given in Table 4. It is concluded that gross current densities of ~1000 Amps/cm$^2$ are acceptable for at least 24T and that there is therefore no reason for the magnets to be unstable. Unstable magnets save only on the copper and would require a more expensive filament design.

Table 5

Blanket and Shield Chacteristics

| | |
|---|---|
| Dimensions - | |
| Blanket | 73.4 cm |
| Vacuum Gap | 1.0 cm |
| Shield | 77.0 cm |
| Blanket Coolant - | Lithium |
| Pressure | 28.1 kgf/cm$^2$ (400 psig) |
| $T_{in}$ | 283°C |
| $T_{out}$ | 483°C |
| Pumping Power | 22 $MW_e$ |
| Structure | 316 Stainless Steel |
| $T_{max}$ | 500°C |
| Maximum Stress at t=0 | 914 kgf/cm$^2$ (13,000 psi) |
| Corrosion Rate | 1500-2500 kg/yr |
| First Wall - | |
| Lifetime | 2 years |
| Neutron Wall Loading | 1.25 MW/m$^2$ |
| Nuclear Heat Load | 12.5 watts/cm$^3$ |
| Shield - | |
| Composition | $B_4C$, Pb, 316 SS |
| Coolant | He, 50 atm, 200°C |

The power supply for the transformer and divertor coils is a major cost item and has not yet been designed in detail. However, energy storgage for 100 second pulses will probably be via superconducting magnets. The energy storage unit must supply 16 MW-hr and this will be coupled with a Graatz Bridge System to transfer this energy.

## D. Blanket and Shield

The blanket of UWMAK-I is shown schematically in Figure 5 and the operating characteristics are listed in Table 5. It is 73.5 cm thick and separated from the 77 cm thick magnet shield by a 1 cm vacuum gap to allow for thermal insulation. The blanket is cooled with Li and the shield is cooled with helium gas.

The general flow pattern of the Li in the heat removal cells, which constitute the first 20 cm of the blanket, is perpendicular to the plasma as shown in Figure 6. The lithium enters the reactor at 283$^{O}$C and leaves at 483$^{C}$C. As stated previously, this relatively low temperature is dictated by the corrosion rate of Li on the structural material, 316 SS. The maximum operating temperature of the 316 SS is limited to ~500 C and this means that 1500-2500 kg of metallic corrosion product must be removed from the primary lithium circuit per year. The coolant cleanup is necessary to avoid plugging the

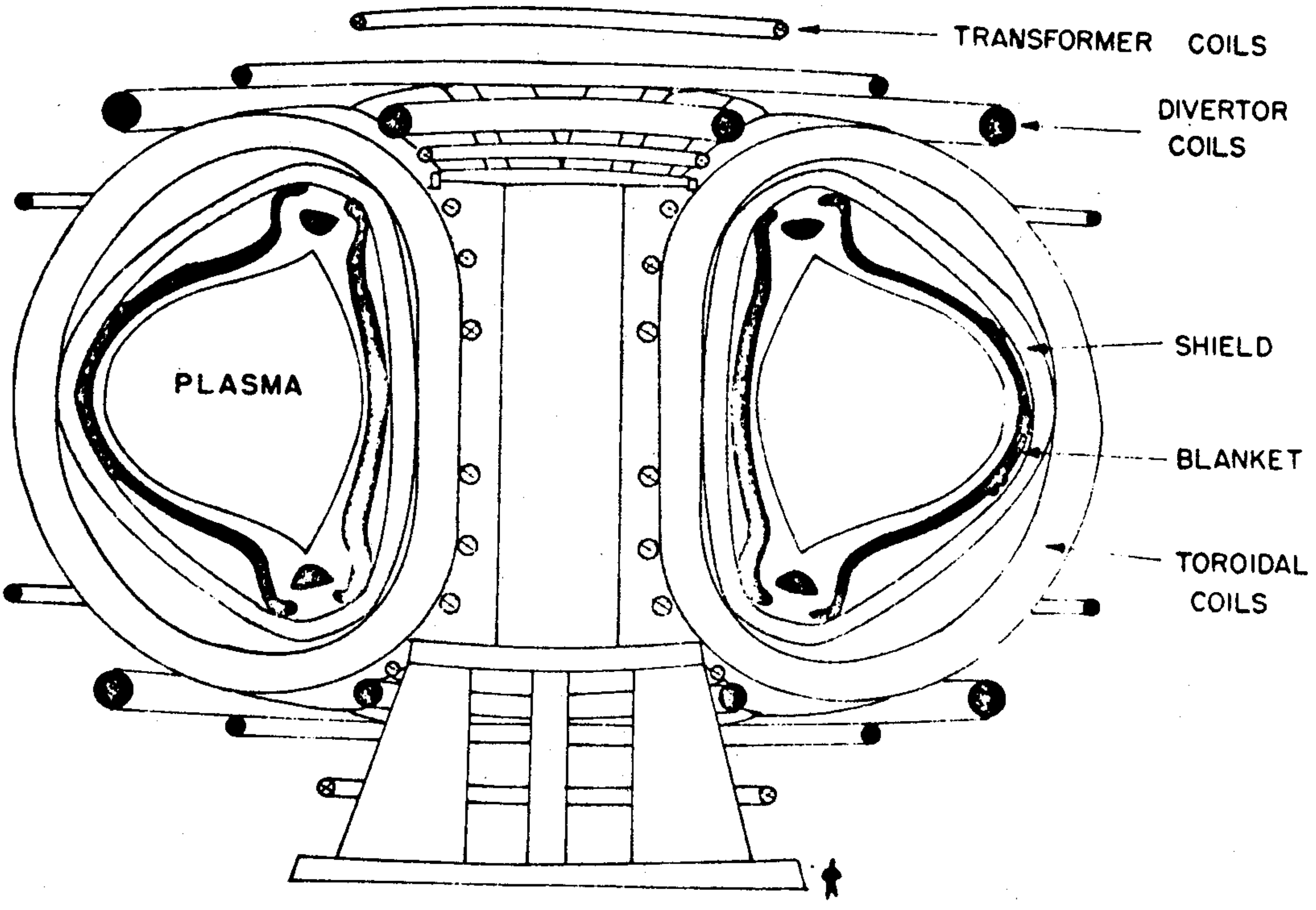


Figure 3 - Cross Section View of UWMAK-I Fusion Reactor

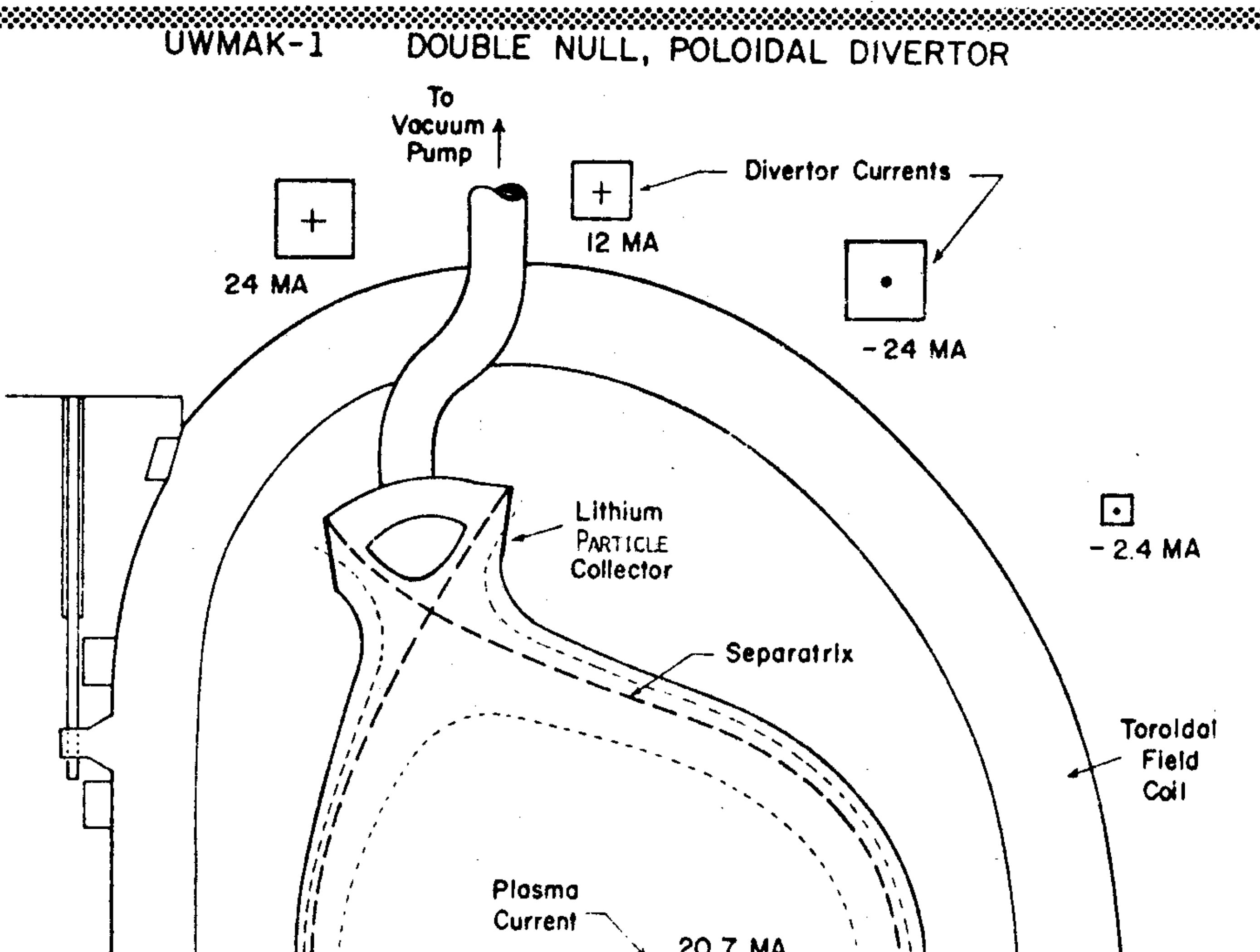


Figure -4

primary heat exchanger and high radioactivity levels in the maintenance areas (5). The maximum pressure in the Li coolant is 28 kgf/cm$^2$ at the reactor inlet and drops to 21 kgf/cm$^2$ at the first wall of the blanket. The total power required to pump the Li is 22 $MW_e$, or ~1.5% of the plant output. This number is quite low due to the present flow design which reduces the average coolant velocity and avoids excessive eddy current losses.

The first wall of the UWMAK-I blanket has been designed to be replaced every two years because of radiation induced embrittlement (9). The first 20 cm has been designed so that they are easily removed and a new section replaced in suitable hot cell facilities. The decision to replace this wall every two years causes a 6% reduction in the plant factor if such an operation takes no more than six weeks each time. Approximately 500,000 kg of 316 SS must be removed and disposed of each time the entire heat removal cells are replaced.

A complete plan for reactor disassembly has been developed and included in the overall plant layout. The

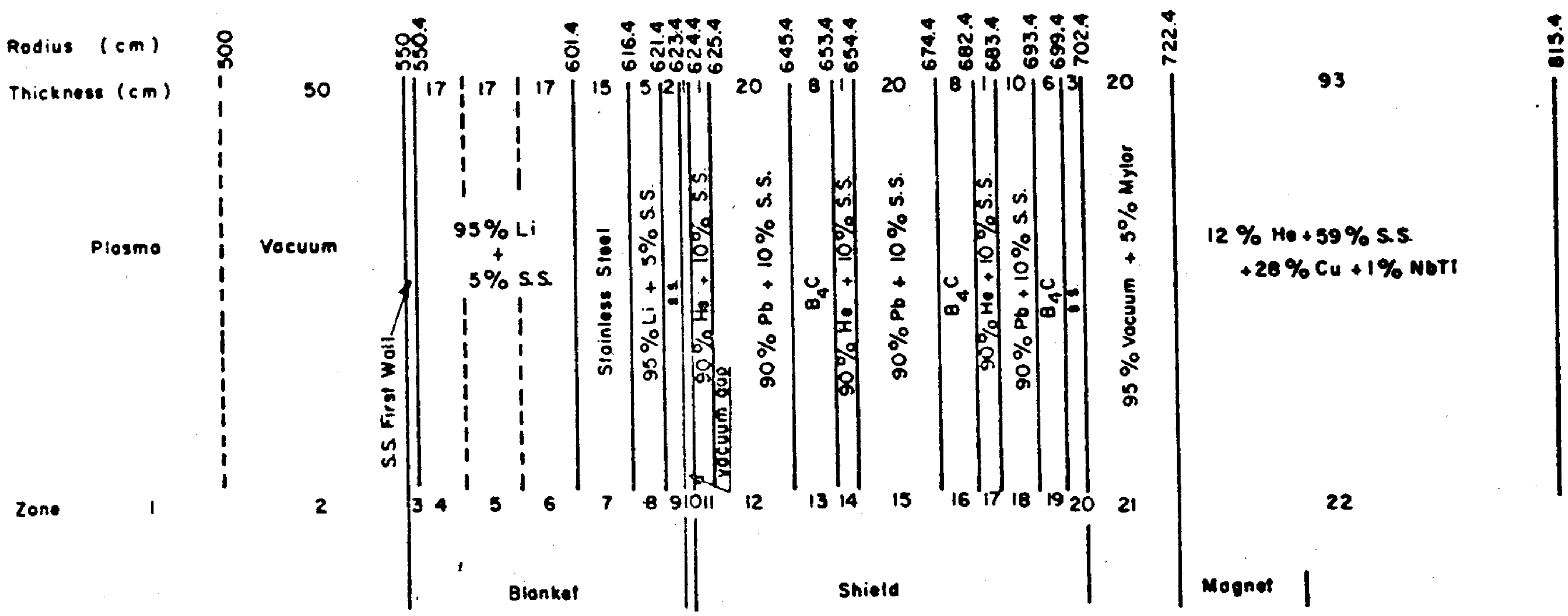


FIGURE 5 - Schematic of UWMAK-I Blanket, Shield and Magnet

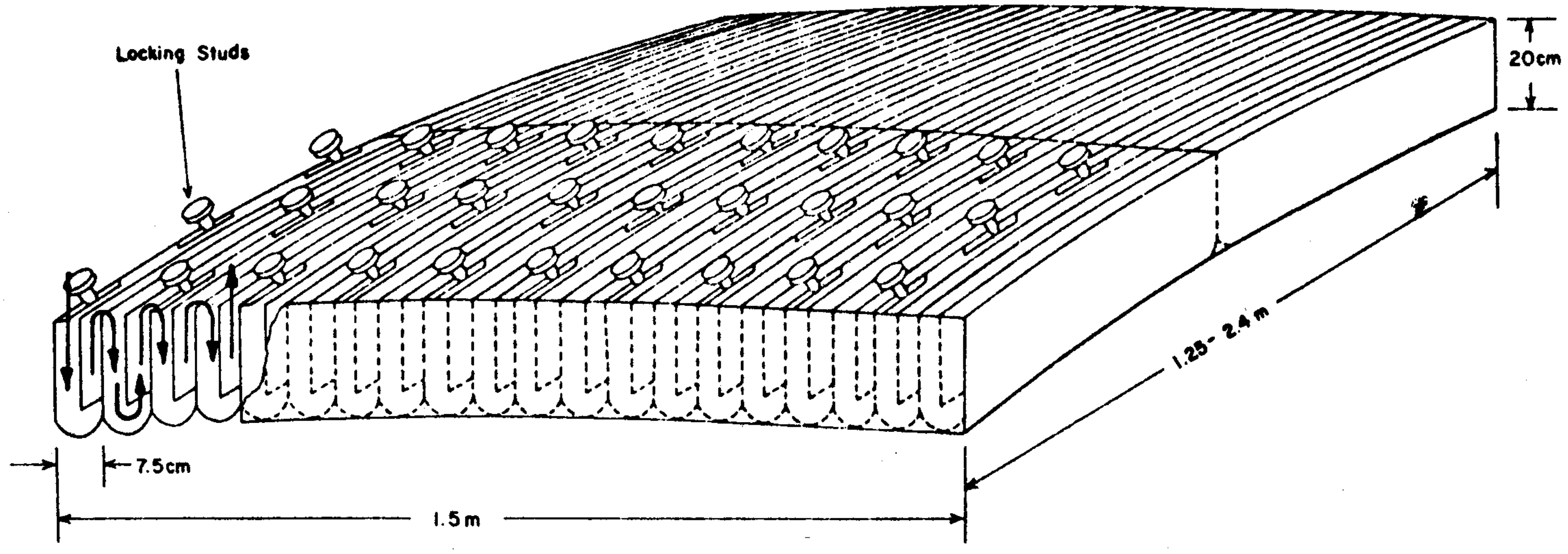
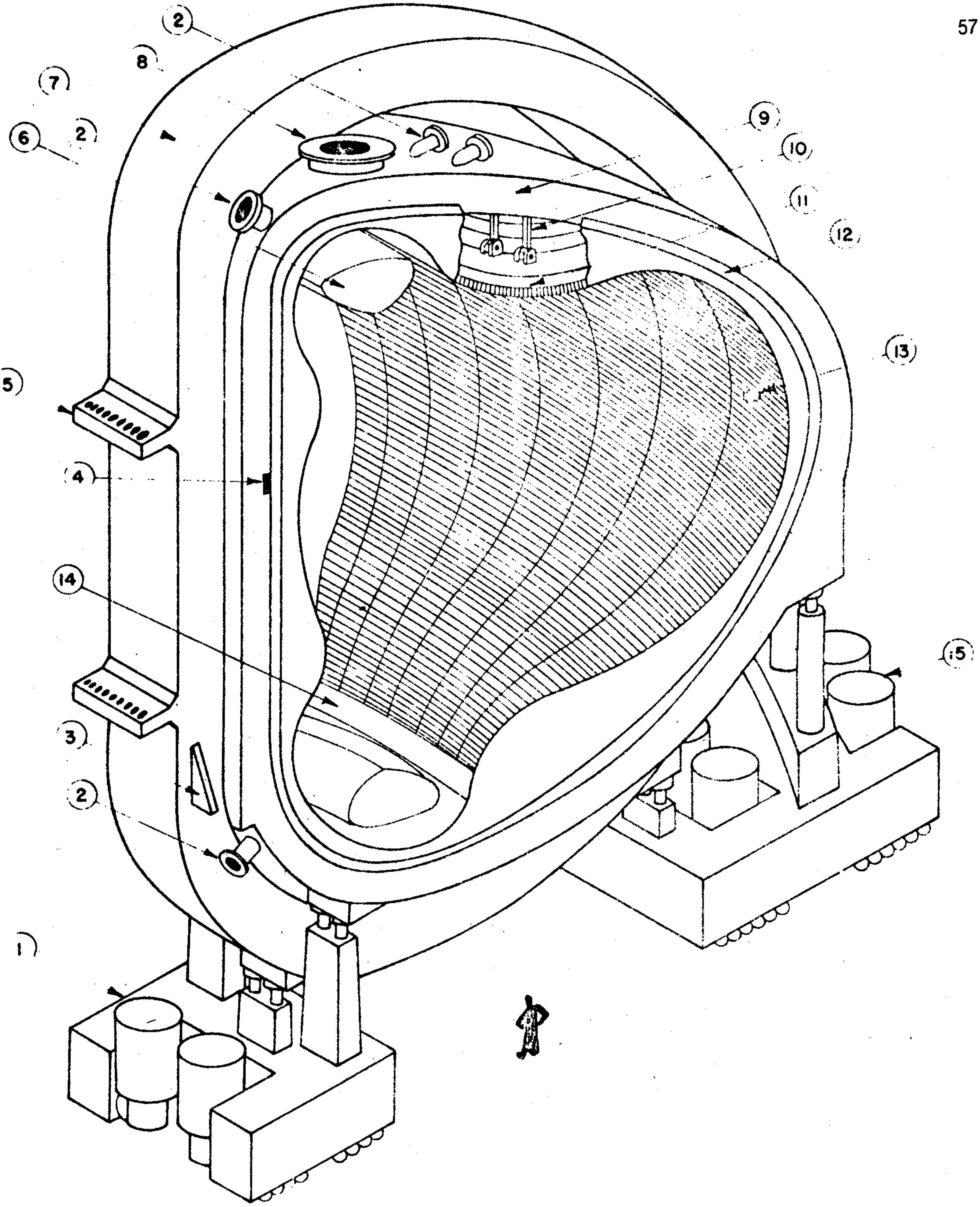


Figure 6 - Isometric View of a Complete Section of Heat Removal Cells
(Locking studs are shown on one half of the section only)



1- Front motorised caterpillar
2- Lithium inlet or outlet
3- Front magnet dewar support
4- Front blanket support bar
5- Magnet support shear beam
6- Vacuum port shield
7- Toroidal magnet in its dewar
8- Vacuum connection
9- Shield
10- Rear blanket support rods
11- Heat Removal cells
12- Blanket seal flange
13- Neutral beam injection port
14- Particle collection plate
15- Rear motorised caterpillar

FIGURE 7

reactor torus has been divided into 12 modules which can be disassembled and withdrawn into the module repair track (Figures 1, 2). Figure 7 shows an isometric view of one module on its motorized vehicle. This module will be transported to a hot cell where the heat removal section (including the first wall) can be safely removed and replaced. The details on the blanket and shield disassembly can be found in Reference 2.

Finally, the shield composed of layers of $B_4C$ and Pb in a stainless steel structure. The shield is cooled with helium gas. (Figure 5) The $B_4C$ is used to slow down and absorb thermal neutrons, and the lead serves to absorb the high gamma fluxes from the blanket. The total heat generated in the shield is 50 $MW_T$.

## E. Neutronics

Neutron and photon transport calculations give a breeding ratio in UWMAK-I of 1.49 with a doubling time on the order of 2-3 months. The tritium breeding is likely to be adequate for all uncertainties in nuclear data or design. The energy attenuation through the blanket and shield is $\sim 4 \times 10^{-6}$. Detailed heating calculations, based on kerma factors from the MACK program (11), were performed and reveal that the energy amplification of the blanket is $\sim 17\%$. It is found that 16.55 MeV of the energy are produced per 14.06 MeV neutron incident on the blanket. Thus, the total energy per fusion reaction, including the 3.52 MeV alpha energy, is 20.08 MeV. This is in contrast to values of 22-27 MeV which have been used in computing power output for fusion plants.

## F. Radiation Damage

Radiation damage studies of the UWMAK-I blanket-shield-magnet combination revealed several severe problems. Table 6 lists the major information from the present work. The most severe problem stems from the fact that the uniform ductility of the 316 SS first wall will be reduced below 1% in 2 years or less at a neutron wall loading of 1.25 $MW/m^2$. (9) This reduction in ductility extends back into the Li header and reflector region, which are 20-50 and 50-65 cm, respectively, from the first wall. (Figure 8) It appears that the headers will have to be changed every 10 years and the reflectors every 15-20 years if one wishes to avoid costly failures during reactor operation. Such a conclusion stems from the displacement damage alone and does not account for the effect of 298 atomic parts per million per year of helium nor the 636 appm per year of hydrogen generated in the 316 SS.

Swelling in a solution treated 316 SS first wall of UWMAK-I due to the production of voids was calculated to be a maximum of 7.9% after two years of irradiation. If 20% cold worked 316 SS were used, the maximum swelling value would drop to 0.25%. Hence, we have decided to use the 20% CW 316 SS in the UWMAK-I design. Detailed calculations through the heat removal cells, the headers and the blanket reflector reveal that even with the use of cold worked steel, swelling values of $<20\%$ could be experienced in 30 years at 30 cm from the first wall. The coolant headers may have to be changed every 10 years and the reflectors every 15 years due to swelling as well as embrittlement.

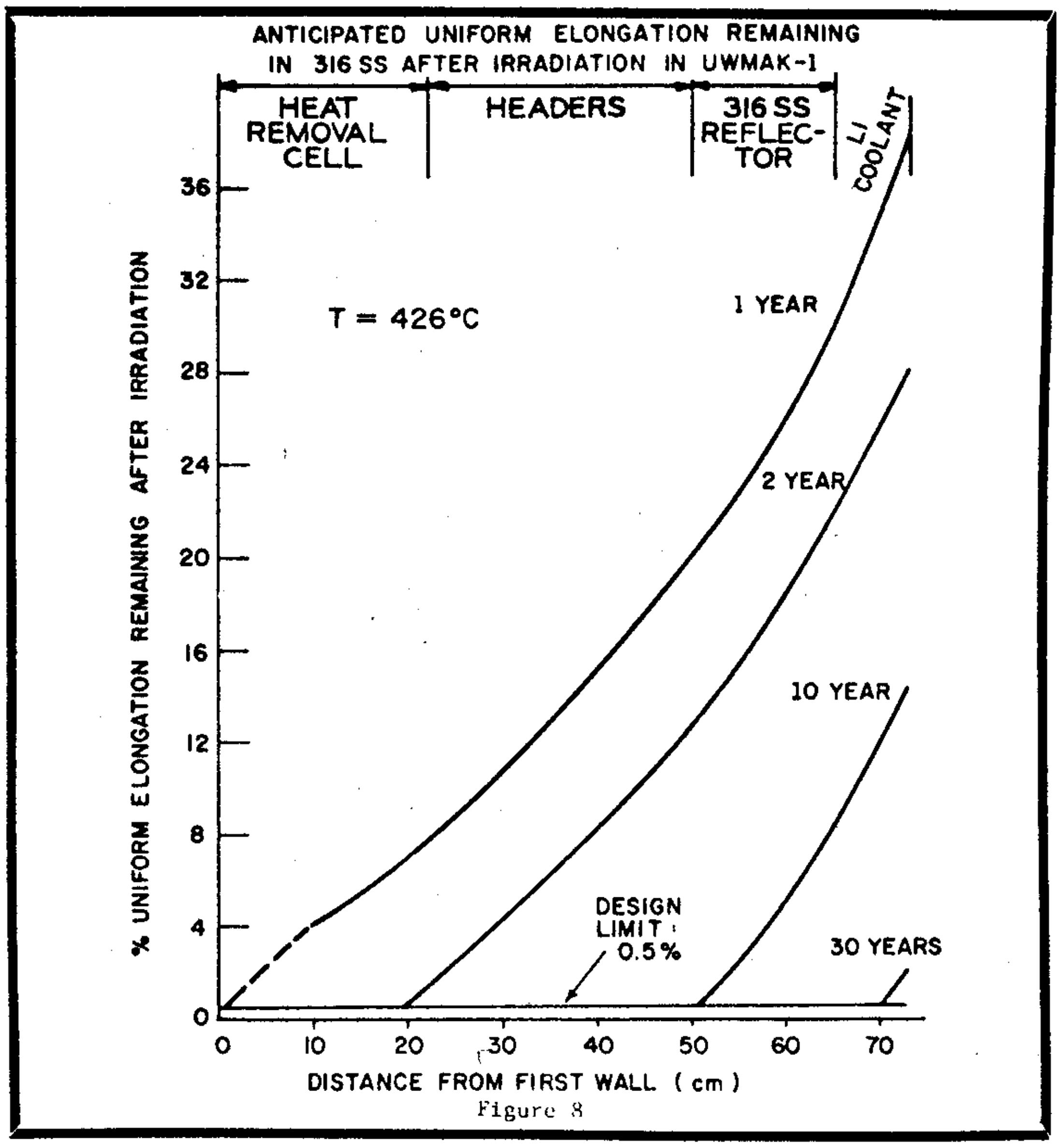


Figure 8

Sputtering and blistering effects on the UWMAK-I first wall reveal no severe problems due to wall erosion if the first wall is replaced every 2 years. The total wall removal rates should not exceed $\sim 0.44$ mm in this time period. The major contribution to wall erosion is from the 14 MeV neutron sputtering that has been recently reported by Kaminsky. (11)

Investigation of radiation induced swelling in the $B_4C$, transmutation of the structural alloy, degradation of thermal and electrical insulating material and reduction in superconducting properties of NbTi reveal minimal effects. Some concern arose about increased resistance in the Cu stabilizer due to the accumulation of point defects at low temperatures, but proper design and periodic annealing at room temperatures can alleviate those problems.

## G. Tritium

The extration of tritium from the Li coolant is accomplished with tritium traps. The breeding ration of 1.49 is so high that doubling times of 3 to 4 months are indicated. However, when fueling, heating and vacuum ports are included in the design, it is expected that the breeding ratio may drop to a lower level. It still may be desirable to "spoil" breeding in UWMAK-I and breed more energy. Such possibilities are being investigated.

A diagram of the tritium removal scheme is shown in Figure 9 with appropriate liquid metal flow rates and temperatures. It is noted that a small amount of lithium is removed from a primary coolant loop, the temperature lowered to ~300 °C and the lithium passed over a yttrium extractor bed. There are two extractors for the primary loop such that the tritium can be extracted from one unit while the other is in service. Only one extraction unit is required for the sodium secondary loop. The pertinent parameters for the tritium system are listed in Table 7. Note that the tritium leakage rate into the steam is ~ 10 curie per day. (12)

## H. Radioactivity

The formation of radioisotopes in the blanket represents two potential hazards; radioactivity and

Major Radiation Damage Information for UWMAK-I

SS First Wall -

Neutron Wall Loading
Max. Displacement Rate
Max. He Production Rate
Max. H Production Rate
Uniform Ductility After 2 Years
Max. Swelling for 2 Years

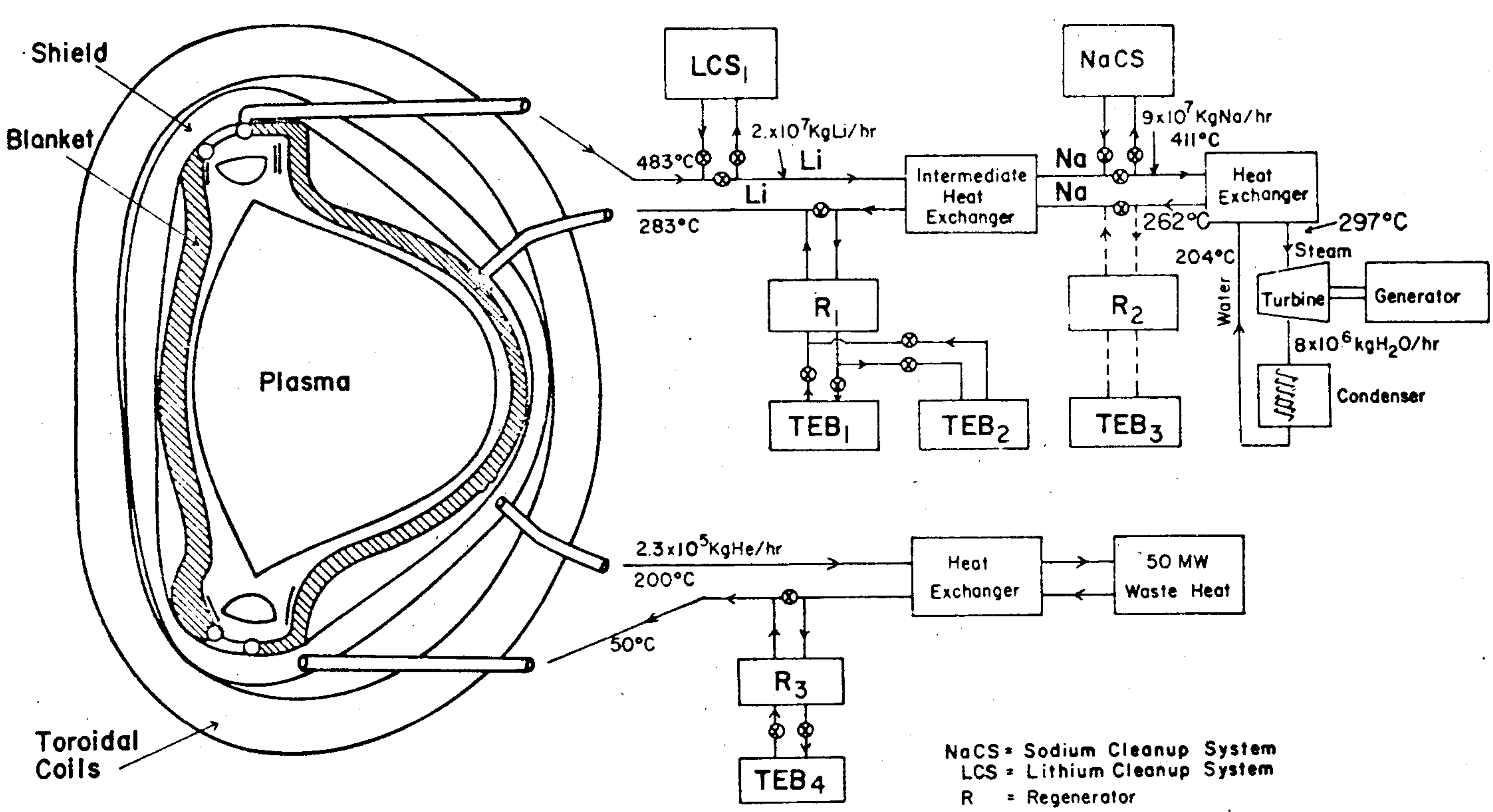
Max. Wall Erosion Rate
Max. Boron Atom Burn Up in $B_4C$

rconducting Magnets -

Max. Change $T_c$ in NbTi
Max. Change $J_c$ in NbTi
Cu Stabilizer
Max. Exposure to Mylar Insulation

1.25 $MW/m^2$
18.2 $yr^{-1}$
298 appm $yr^{-1}$
636 appm $yr^{-1}$
<0.5%
7.9% (ST 316 SS)
0.25% (20% CW 316 SS)
0.22 $mm\text{-}yr^{-1}$
$3.2 \times 10^{19}$ $cm^{-3}yr^{-1}$

<1°K (30 years with peri
<5% (30 years with peric
$6 \times 10^{-5}$ dpa $yr^{-1}$
$2.8 \times 10^4$ Rad $yr^{-1}$



NaCS = Sodium Cleanup System
LCS = Lithium Cleanup System
R = Regenerator
TEB = Tritium Extraction Bed
Flow Rates are for Whole Reactor

Coolant Loops for
Wisconsin Toroidal Fusion Reactor – UWMAK-I

FIGURE 9

## Table 7

## Summary of Tritium Extraction System Characteristics[(a)]

| System | Temp. Range°C | Extraction Method | Tritium Accumulation per Day (kg) | Tritium Leakage Ci/day | Tritium Concentration ppm (wt.) | Tritium Inventory (kg) |
|---|---|---|---|---|---|---|
| Primary Lithium | 283-483 | Yttrium Metal Bed | 1.05(b) | 10.1 | 5 | in Li 8.7<br>in beds 1.0 |
| Secondary Sodium | 261-411 | Yttrium Metal Bed | ~0 | --- | $3.3 \times 10^{-4}$ | in Na $2.5\text{x}10^{-4}$<br>in beds ~0 |
| Divertor | | | | | | |
| Lithium | 200-325 | Yttrium Metal Bed | 7.4 T + 5.0 D | $2\text{x}10^{-4}$ | 0.24 | in Li $8\text{x}10^{-}$[illegible]<br>in beds 3.5 |
| Sodium | 190-265 | | — | — | $3 \times 10^{-4}$ | in Na $2\text{x}10^{-5}$ |
| Divertor Vacuum | 25 | Charcoal cooled liq. He | 0.3 T + 0.2 D | $1\text{x}10^{-4}$ | N.A. | 0.3 |
| Helium | 50-200 | Metal getter | $1.1 \times 10^{-6}$ | low | N.A. | low |
| | | | Total | 10.1 | Total | 13.5 |

(a) Based upon thermodynamic calculations; no kinetic considerations

(b) At maximum breeding ratio of 1.49

N.A. - Not Applicable

## Table 8

## Major Radioactive Isotopes in UWMAK-I with Various First Wall Blanket Materials(a)

| System | Isotope | $t_{1/2}$ | Activity Ci/kW(6) | Maximum Permissible Concentration μCi/cm$^3$ | Biological Hazard Potential km$^3$ of air/kW(t) |
|---|---|---|---|---|---|
| Fusion-all(c) | $H^3$ | 12.3y | 60 | $2 \times 10^{-7}$ | 0.30 |
| 316 Structure only | $V^{49}$ | 331d | 0.67 | $1 \times 10^{-10}$ | 6.7 |
| | $Fe^{55}$ | 2.94y | 140 | $3 \times 10^{-8}$ | 4.6 |
| | $Co^{58}$ | 27d | 29 | $2 \times 10^{-9}$ | 14.5 |
| | $Ni^{57}$ | 1.5d | 1.1 | $1 \times 10^{-10}$ | 11 |
| | $Mn^{54}$ | 313d | 24 | $1 \times 10^{-9}$ | 24 |
| | $Co^{60}$ | 5.25 | 4.7 | $3 \times 10^{-10}$ | 15.6 |
| Total(d) | | | ~310 | | ~80 |
| Nb-1Zr Structure | $Nb^{92m}$ | 10.2d | 152 | $1 \times 10^{-10}$ | 1,520 |
| | $Nb^{95m}$ | 3.75d | 50 | $1 \times 10^{-10}$ | 500 |
| | $Nb^{95}$ | 35d | 42 | $3 \times 10^{-9}$ | 14 |
| | $Sr^{89}$ | 54d | 38 | $3 \times 10^{-10}$ | 126 |
| Total(d) | | | ~300 | | ~2,200 |
| V-20Ti | $Sc^{48}$ | 1.83d | 12.1 | $5 \times 10^{-9}$ | 2.5 |
| | $Ca^{45}$ | 152d | 2.6 | $1 \times 10^{-9}$ | 2.6 |
| | $Sc^{46}$ | 85d | 1.87 | $8 \times 10^{-10}$ | 2.3 |
| | $Sc^{47}$ | 3.4d | 1.58 | $2 \times 10^{-8}$ | 0.079 |
| Total(d) | | | ~56 | | ~9 |

(a)Neglect all isotopes with $t_{1/2} < 1$ day.

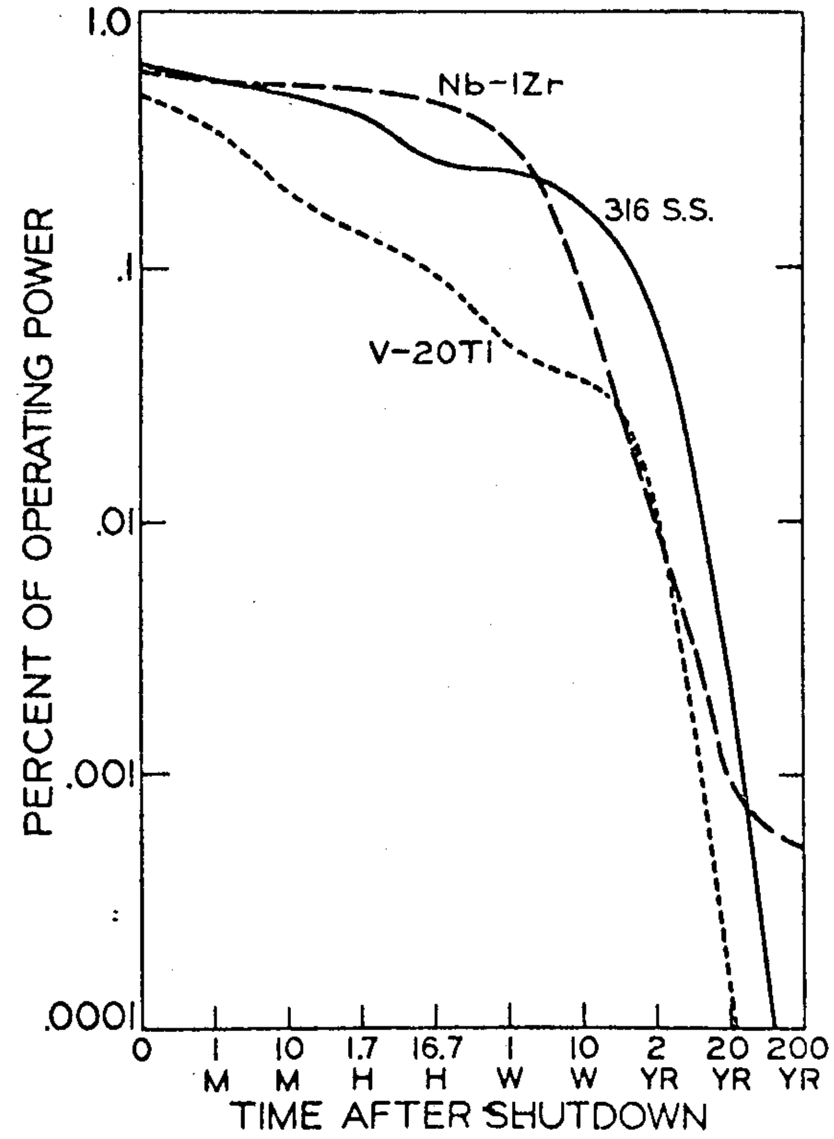
(b)10 year exposure

(c)Assume total plant inventory at 30 kg (13.5 kg in reactor and 16.5kg external).

(d)Including isotopes not listed.

afterheat. Table 8 summarizes the important radioisotopes produced per $kW_{th}$ in UWMAK-I and their maximum permissible concentration (MPC) in $km^3$ of air per curie. A biological hazards potential (BHP) was calculated by dividing the activity by the MPC. The BHP's for 316 SS in Table 8 are compared to alternate materials for CTR blankets. It can be seen that 316 SS is considerably better than Nb-1Zr from the standpoint of BHP but that a V-20Ti system would be even more desirable. Detailed analysis of the specific radioisotopes and their half lives are examined in References 2 and 14.

The decay of the radioisotopes mentioned above generated heat that must be dissipated to avoid severe temperature problems in the event there is a loss of flow of the coolant. Pertinent information on afterheat in UWMAK-I with heat removal cells of three different materials is shown in Figure 10. The afterheat after 10 years of operation at 5000 MWT is ~31 MW for 316 SS, ~30 MW for Nb-1Zr and 23 MW for V-20Ti at shutdown. This radioactivity drops off quite rapidly for the vanadium system but remains rather stationary in 316 SS and Nb-1Zr for 1-2 years. Both of these latter systems show a considerable drop in the 2-20 year period decaying to less than 50 kW in 100 years. Calculations of the maximum temperature rise rate under adiabatic conditions reveal values on the order of ~0.1°C $sec^{-1}$ More realistic approximations of the rate of heat leakage reveal the maximum value is unlikely to exceed 0.01°C $sec^{-1}$ indicating that emergency cooling requirements are minimal.



Afterheat in UWMAK-I

Figure 10

## I. Power Cycle

The pertinent temperature and flow rates for Li, Na and steam are shown in Figure 9 for UWMAK-I. Detailed analysis of the steam cycle will be reported elsewhere (14) but an overall efficiency of ~30% (including circulating power requirements of 8.4%) has been calculated.

## J. Cost Analysis

A preliminary cost analysis of the UWMAK-I system has been completed (15). The basic assumptions that have been used are an 80% plant factor, 8% interest during a five year construction time and 15% return on capital. The resulting analysis reveals that the overall plant costs could be as much as $900-1000 per $kW_e$ and the cost of generating electricity may be in the neighborhood of 20 mills/kw-hr. Further optimization of the UWMAK-I reactor costs is in progress and it is hoped that the cost may be reduced by 10-20%. It is encouraging that these preliminary estimates of fusion reactors are not particularly out of line with first generation fission reactors.

## III. CONCLUDING REMARKS

Even though we have attempted to minimize the amount of extrapolation that would be required to construct a reactor like UWMAK-I, it is certainly recognized that there are areas which still contain large unknowns. These areas will be more clearly delineated in another paper in this volume but two major areas stand out: plasma physics and materials technology. A great deal of investigation is still required to understand the behavior of D-T plasmas containing helium, the effects of impurities, fueling, and loss modes. It is also imperative that we understand the mechanisms of radiation damage of CTR materials if we ever expect to build safe, economical fusion reactors.

Finally, it should be especially noted that the real usefulness of the design effort which we have just summarized lies not with the hope that such a system will actually be built, but rather in focusing attention on areas of technology that require further work before meaningful reactor studies can be completed. We fully expect that some features of UWMAK-I design will be changed as new discoveries are made in plasma physics, material behavior, and reactor technology in general. Hopefully, other laboratories will also complete detailed studies, and by noting the best features from many systems, we will be able to begin the design of the first real fusion power plant in the 1980's.

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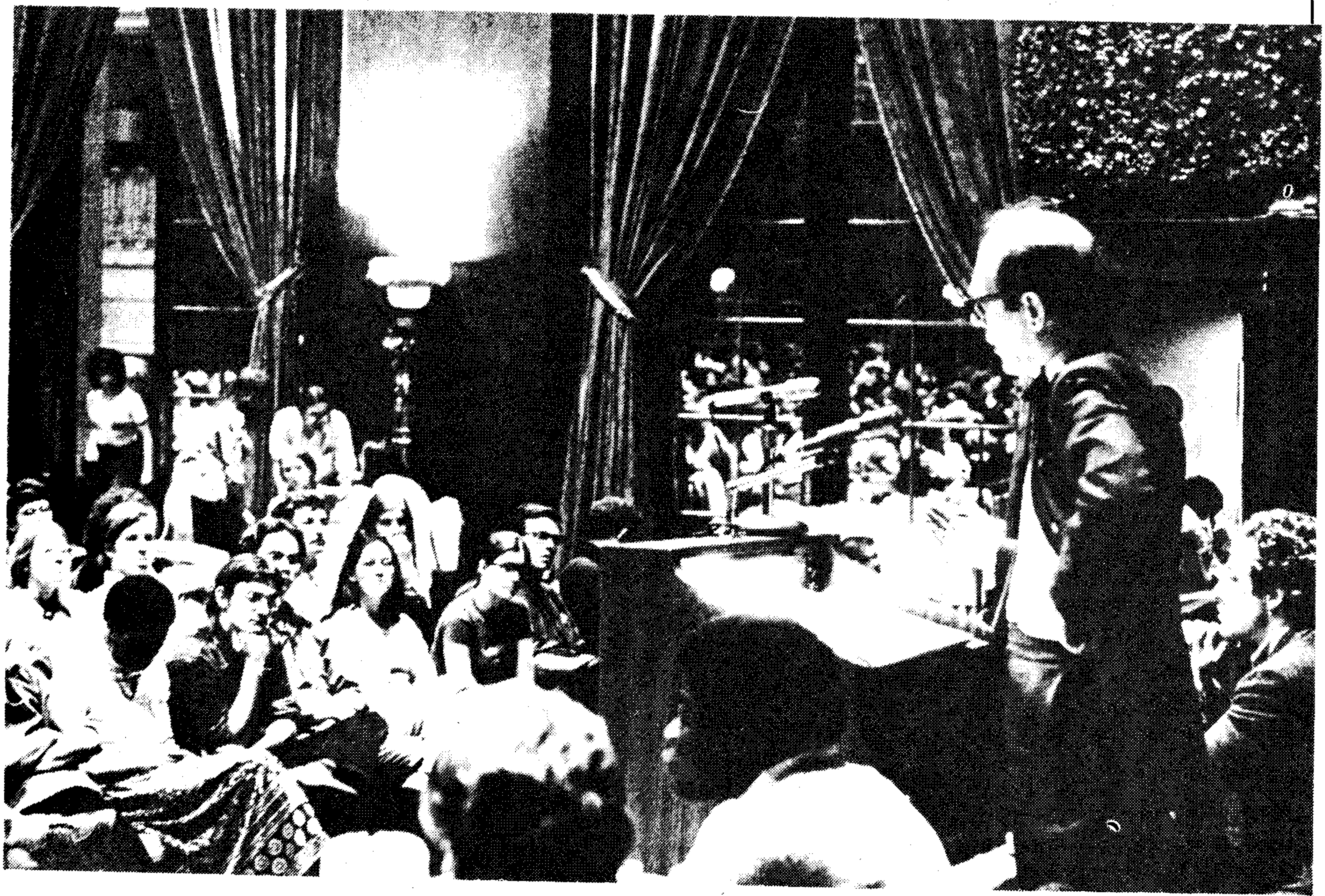


# Technological Implications for Tokamak Fusion Reactors of the UWMAK-I Conceptual Design

Robert W. Conn and G.L. Kulcinski

Paper presented at the First Topical Meeting on the
Technology of Controlled Nuclear Fusion held in San Diego - April 14-18, 1974

## 1. Introduction

A detailed description of the conceptual Tokamak fusion reactor, UWMAK-I, (1) has been presented in another paper in this volume. The purpose of the UWMAK-I study has been to carry through a conceptual design in sufficient detail to identify and quantify some of the major technological problems that will face the designers of fusion power reactors. Some problems are specific to the Tokamak confinement concept but many are applicable to deuterium-tritium fueled fusion reactors in general. In this paper, we consider the major conclusions and technological implications of this work. The paper is organized such that each major technical area is treated separately but the impact of problems in one area on those in other areas is considered throughout.

## 2. Plasma

It is clear that a number of serious uncertainties remain in the plasma physics and operation of Tokamak devices and these will have a serious impact on the ultimate design and operation of Tokamak fusion reactors. These uncertainties relate to the startup of a large Tokamak discharge, the plasma scaling laws that will ultimately govern the plasma physics of the reactor regime, the effects of impurities and impurity control, the operation and efficiency of divertors for impurity control, and methods for fueling the plasma. The last two areas are critical if long burn times, on the order of several minutes to an hour, are to be achieved.

The startup of a large Tokamak discharge is an important open question. The use of a moving limiter for UWMAK to perform such a function is being studied presently (2) and such operation will be studied on PLT. (3) The use of an expanding magnetic limiter is also a possibility and this may be studied on the Poloidal Divertor Experiment currently being designed. (4) For UWMAK-I, we have studied the trade off between the startup time and the peak power required from an energy storage unit. The energy required to provide the requisite transformer action is 16 MW-hr based on a plasma resistivity of 3.5 times the Spitzer value. This anomolous increase is to account for either neoclassical effects (5) or the presence of impurities. Table 1 summarizes the results. It is assumed that it will be possible to purchase 500 MWe from the line when a reactor such as UWMAK-I is operational. The National Accelerator Laboratory now purchases 200 MWe from Commonwealth Edison of Chicago. The conclusion is that there exists a serious competition between short startup times and the desire to minimize the cost and size of energy storage systems for Tokamaks.

The effective plasma resistivity impacts on the transformer design as well as the stored energy requirement. The design discussed in Reference 1 can accomodate anomolous resistivities up to a factor of 8 times the Spitzer value before the maximum field of 8.6 Tesla appears at any of the transformer coils.

**Table 1**

**Current Rise Time and Energy Storage**

| | | | |
|---|---|---|---|
| 1 | .139 | 15.9 | $1 \times 10^{5}$ |
| 10 | 1.39 | 14.6 | $1 \times 10^{4}$ |
| 50 | 6.94 | 9.1 | $2 \times 10^{3}$ |
| 100 | 13.9 | 3.2 | $10^{3}$ |
| 200 | 16.0 | 0. | $5 \times 10^{2}$ |

Plasma heating using neutral beams has been studied for the UWMAK-I system and the questions of the profile for beam energy deposition, beam energy requirements for penetration, and beam power requirements to achieve ignition or a prescribed heatup rate have been analyzed. (6) The analysis, based on pseudoclassical electron heat transport, (7) neoclassical ion heat transport, (8) and injection tangent to the magnetic axis, shows that large Tokamak reactors such as UWMAK-I can be ignited at low density ($\sim$3x10 13 particles/cm3), using moderate levels of neutral beam power (10-75MW), beam energies of several hundred KeV, and in times on the order of seconds. Ohmic heating alone is insufficient to ignite the plasma. For UWMAK-I, a 500 KeV beam of deuterons or tritons is adequate to provide injected power deposition profiles that are peaked on axis. Lower energy beams, such as 100 KeV, do not penetrate the plasma and thus yield temperature profiles peaked towards the plasma edge. However, in terms of heating, such beams would be adequate and can actually produce more rapid heatup rates. It has been found, for example that a 100 KeV beam produces a faster plasma heatup rate following termination of injection than a 350 KeV beam. (6) The low density beam heating phase is used to enhance beam penetration while reducing plasma losses. From this analysis, neutral beam heating appears to be an effective way to ignite a large power reactor such as UWMAK-I. It will be important, however, to assess the effects of alternate plasma scaling laws on these results. This work is in progress.

We noted previously that plasma operation in UWMAK requires confinement times that are several hundred Bohm times but are $\sim$2-3 orders of magnitude shorter than neoclassical confinement times. These requirements are for plasma operation at quasi-steady state during a burn time. The most economical temperature range for the plasma operation in a $\beta$ -limited plasma is 10-20 KeV. If the scaling on $\tau$ E and $\tau$ c are proportional to $T^{1/2}$ then an energy equilibrium in the 10-20 KeV range is thermally unstable. Thermally stable operating conditions are possible at higher temperatures ($T_i >$25KeV) but require larger toroidal magnetic fields to produce the same power. For UWMAK-I, thermally stable and unstable equilibria have been calculated and operation at the stable point would require magnets that are approximately $\$100\mathrm{x}10^{6}$ more expensive than for operation at the unstable point (still within NbTi superconductor technology.)

The method of producing thermally stable plasma operation in the desired n, T, $\tau$ range remains an open question. We have recently examined the effects of predicted microinstabilities (9) on Tokamak plasma operation. (10) In particular, using the predicted scaling for the dissipative trapped ion mode given by Dean et. al. (11) it is found that thermally stable plasma operation can be attained for temperatures in the range from 10 to 20 KeV. As a quantitative example, using UWMAK-I machine parameters for q, $\beta_\theta$ , A, $B_\phi$ (on axis), and the plasma current, Ip, of 20.7 MAmps, a thermally stable plasma equilibrium producing 5000 $MW_{th}$ occurs at a plasma temperature of 14.5 KeV for $Z_{eff} = 1$. No impurities are purposely added to the plasma. Should $Z_{eff}$ be larger, the stable equilibrium temperature increases.

When the confinement time is the order of several seconds, as is implied by trapped ion mode scaling, the problem of fueling becomes very important if long burn times, such as the 90 minute burn time for UWMAK, are to be achieved. Fueling with large pellets ($\sim$2mm diameter D-T pellets) appears formidable if the accelerating velocities required for penetration are to be achieved. (12) Larger pellets will constitute either too large a fraction of, or actually exceed, the number of particles in the plasma. Little effort has been devoted to detailed analysis and experiments in this area and more work is required to better understand the physical processes involved in pellet fueling of reacting plasmas.

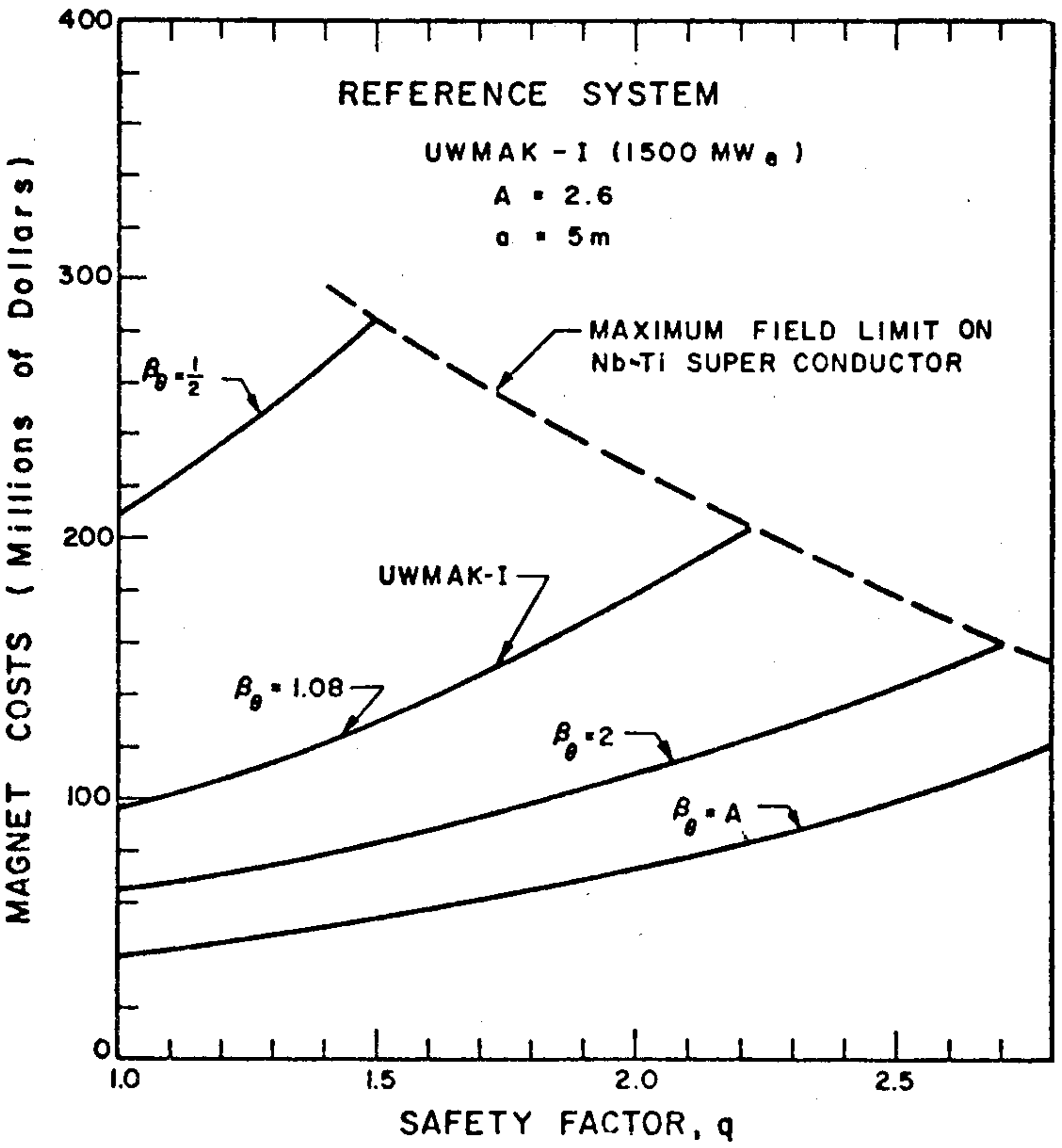
The plasma stability factor, q, and the plasma Beta, $\beta$ , are critical parameters for Tokamaks and while $q > 1$ (the Kruskal-Shafranov limit) is generally accepted, present devices generally have q at the plasma edge greater than 3. In addition, the poloidal beta, $\beta$, ($\beta$ in the weak magnetic field) is usually around 1/2. It is important to know the upper limit on $\beta_\theta$ and the lower limit on q for stable plasma behavior since this strongly effects plant economics. Figure 1 shows the scaling of magnet costs (toroidal field, transformer and divertor field coils) as a function of the safety factor, q(a), for different poloidal beta limits using UWMAK-I as the reference point. Along a constant $\beta_\theta$ line, the plasma current is fixed which means the cost of the transformer and divertor windings are also fixed and only the toroidal field magnet costs vary. On the other hand, *all* magnet costs scale as one moves vertically along a line of constant q since both $\beta_\phi$ and $\beta_\theta$ change such as to keep the ratio constant. It is clear that the best case is the line of largest constant $\beta_\theta$, taken here to be $\beta_\theta \doteq A$ The right hand scale translates magnet costs to dollars per kWe and all costs are for NbTi superconducting magnets. Along a constant $\beta_\theta$ line, q can only be increased by increasing the toroidal field, $\beta_\phi$, which means increasing the maximum field at the toroidal field magnets. We have set 100 Kilogauss as the upper limit for NbTi coils (allowing for pumping on the helium) and have indicated this by the hatched line in Figure 1. For $\beta_\theta$ and q combinations above this line, the superconductor must be changed, the technology will change, and the costs will show a different scaling. It suffices to conclude that there is strong incentive for achieving high $\beta$ and low q in a Tokamak (also for other $\beta$-limited devices, such as stellarators) and the cost figures give some quantitative indication of the economic penalties involved in various choices.

Long burn times also require control of impurities in Tokamak plasmas. Divertors such as that included for UWMAK-I may be the basis for such impurity control and can also serve to protect the first wall from bombardment by energetic particles. The advantages of the double null poloidal divertor, described in Reference 2 and elsewhere, (13) are that it is compatible with the desire for a small aspect ratio, it produces a vertically elongated D-shaped plasma that is consistent with the D-shaped toroidal field coil design, and it leads to low ratios of maximum field to toroidal field in axis, the value for UWMAK being 2.25. This last point is quite important since it allows the use of NbTi superconducting magnets and thus does not require a large extrapolation of present technology.

Poloidal divertors which preserve axis symmetry appear feasible but many open questions remain. The major questions that remain are the efficiency of such divertors for collecting particles diffusing out of the plasma, ($\sim 3.5 \times 10^{22}$ particles per second for UWMAK) and metallic atoms coming off the walls. Both experiment and analysis are required to better understand the physics in the region between the plasma edge and the first wall, and including plasma-wall interactions, the effects of neutral gas in the diverted field zone, the impact of neutron sputtering, (14) and the blistering and sputtering caused by charged particle bombardment of the first wall.

## 3. Magnets

Large bore, superconducting magnets are essential for the economic development of fusion power. The toroidal field coils design developed for UWMAK-I (1) is based on the recognition that complete cryogenic stability is the only viable design at this time. The alternative of using unstable magnets requires considerable development before any reliability can be predicted. In addition, from the UWMAK-I design, it appears that the required toroidal field on axis in Tokamaks can be achieved with current densities of about 1000 Amps/cm$^2$ , a typical cryogenically stabilized value.



Many magnet shapes were possible for UWMAK-I but only two were seriously considered: A circular cross section (15) with external reinforcement rings to resist bending and a "D" shaped magnet (16) which provides a constant tension winding region without external rings. The constant tension design makes best use of a uniaxial stressed member and for this reason, and to accomodate the diverse requirements of the plasma and divertor, the constant tension design was chosen. Figure 2 shows the outline of this shape as curve (a), which is the true "D" shape and the only one for which the tension is constant for all portions of the conductor, including the straight vertical inner portion. For curve (b), the tension is constant only over the portion from the outside up to point B. For curve (c), the small starting radius and smaller tensile load does not permit the shape to reach the desired inner dimension. (This is constant tension from the outside to point C but from C to O in Figure 2, the extra magnetic loading cannot be carried by tension in the winding frame and is instead transmitted to the central core.) With these options, it has been found possible to economically accomodate various plasma shapes by modifying the basic constant tension "D" shaped magnet. Also, the effects of winding thickness have been included. It is also proposed to prestress the conductor during winding in order to make better use of the stainless steel. Shape (c) was chosen because it is the only one which assures the retention of the prestress.

Conductor design questions have also been addressed. It appears extremely difficult to conceive of winding such large bore, high field magnets from wire or tape. Several large conductor designs (~2cmx2cm) have been considered (17) and a composite conductor of NbTi in copper sized to carry the total design current at 5.2°K was chosen. This conductor will be inserted into spiral grooves of varying width and depth on the face of roged, stainless steel pancakes. The magnets are then constructed by stacking individual pancakes (18) and the design uses cooling on both sides of the individual "D" shaped discs.

A liquid helium refrigeration system has been sized to meet the total magnet system heat loss rate of 11 kW and is found to be a relatively small cost factor, namely, about 5% of the total costs of the transformer, divertor, and toroidal field coils. However, the supply of helium is a potential problem area. The magnet system requires 250,000 liters with 200,000 liters in storage to allow for 24 hours of operation during a refrigerator malfunction.

The magnetic fields external to the plant coming from stray toroidal fields and from the divertor and transformer coils as described in I are also a potential problem. In UWMAK, the poloidal field associated with the system of toroidal currents, including the plasma current, are the main contributors to the field external to the plant. The mod B contour plot shown in Figure 3 indicates that the field drops under 1 gauss at about 500 meters and is falling off as a dipole-field. The average value of the earth's magnetic field in Wisconsin is approximately 1/2 gauss.

## 4. Neutronics

The neutronics and photonics studies of fusion reactor blankets and shields is central to the analysis of fusion power reactors. The neutronics studies for UWMAK-I (1) have shown that tritium breeding in stainless steel, lithium cooled systems is large enough that most conceivable variations in nuclear data are unlikely to prevent such systems from breeding. This is to be coupled with the fact that short doubling times, on the order of months, are possible in fusion systems even at lower breeding ratios than the 1.49 value for UWMAK. The same conclusion has been found if Nb, V, or Mo were substituted as the structural material. Variational calculations have shown that alterations in the percentage of structural material in the tritium breeding zones away from 5%, as used in UWMAK, do not prevent SS, V, or Mo systems from breeding. (19) However, 15% Nb in the breeding zones lowers the breeding ratio to 1 in a UWMAK-type blanket.

Methods for calculating space dependent nuclear heating in fusion systems have been developed at Wisconsin (20) and the results have shown that the total energy per fusion reaction is about 10% lower than the nominal value of 22.4 MeV often assumed in fusion work. This is particularly relevant since the reactor

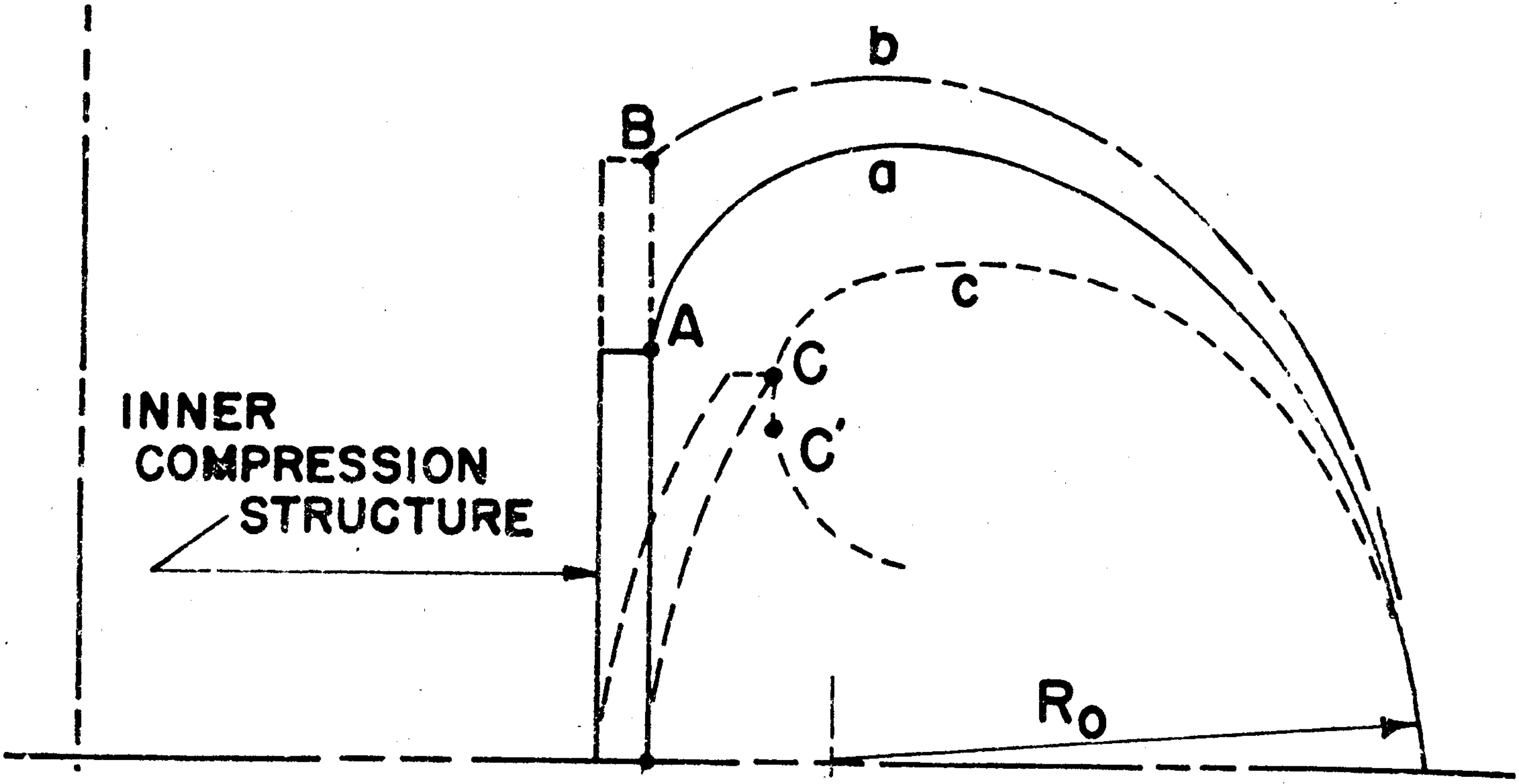


Figure 2. Three typical "D" Shaped Magnet Designs. Only curve 'a' yields constant tension for all portions of the conductor.

power output is directly proportional to this value. From these studies, we have also concluded that enrichment of natural Li in $^6$Li does *not* significantly effect energy multiplication and, given that it is an expensive process, such enrichment does not produce an economic gain. For UWMAK-I, enrichment to 50% $^6$Li increases the energy multiplication by less than 1% over the natural lithium case. The energy produced can be improved, however, by addition of Be in the blanket and this appears economical. For example, 4 cm and 10 cm of Be increases the total energy production by 9% and 19%, respectively. The additional costs appear to be less than half the decrease in cost per unit power. On the other hand, as we shall discuss shortly, the low reserves of Be both inside and outside the U.S. appears to foreclose the possibility of widespread use of Be in a $10^6$ MWe fusion economy.

The reflector in the UWMAK-I blanket is stainless steel rather than graphite. A SS reflector improves energy multiplication and energy attenuation. It also allows for a thinner reflector zone which makes the blanket and shield thinner and brings the magnets closer to the plasma, thus saving on magnet costs. The breeding ratio is lowered slightly but 1.49 for UWMAK is perhaps too high in any case.

The proposed shield design is based on optimization studies to minimize cost when the costs of the magnets, the shield itself, and refrigeration for the magnets, are considered. The optimum materials choice for the shield is 70% lead and 30% boron carbide. In practice, 20% stainless steel has been included for structure and the lead content has been lowered to 50%. The shield thickness of 77 cm yields a blanket-shield system thinner than is usually employed. The blanket could actually have been even thinner and still produced adequate tritium breeding because the blanket size was governed by heat transfer and coolant flow considerations.

Another area of considerable importance which we have studied is the gas production rates as a function of position in fusion blankets. In the first wall of UWMAK, (1) the hydrogen production rate is 636 appm/year and the helium production rate is 298 appm/year. The implications of such high production rates on the materials in UWMAK-I will be discussed shortly (see alse, reference 21). However, a relevant point here is to note that a serious problem in this area is the paucity of gas producing reaction cross sections themselves. This has been pointed out in a recent comparative study of various fusion reactor blanket designs, (22) and also discussed by Barschall. (23) In view of the magnitude of the gas production rates and given the relevance of such information to radiation damage (21) in fusion systems, experiments are required to obtain this data.

## 5. Radiation Damage

The effects of radiation on the materials in fusion reactors has been recognized for some time as perhaps the major technological uncertainty aside from the plasma physics itself. The radiation damage studies for UWMAK-I have allowed us to quantify the extent of certain types of damage and to point to areas of large uncertainty. The major information from the UWMAK-I study was reported in Reference 1. This included information on void swelling, gas bubble swelling, irradiation effects on yield strength, transmutation effects, loss of ductility and surface effects.

The most severe limitation on the lifetime of the first wall of the UWMAK-I reactor is the loss of uniform ductility below a design value of 0.5%. This embrittlement is the result of two mechanisms; helium embrittlement and matrix hardening. (24-27). Helium embrittlement results from the generation of helium gas within the matrix by $(n, \alpha)$ reactions and the collection of helium gas bubbles at grain boundaries. These bubbles can grow under the action of applied stress by diffusional properties until the grain boundaries fail. Ultimately, the bubbles may lead to failure by assisting crack nucleation at second phase particles within the boundaries. This effect is dominant at high temperatures ( >0.5Tm or >650°C in steel). Matrix hardening can lead to premature failure by forcing most of the deformation to be absorbed by the grain boundaries. Such an effect results in excessive grain boundary shearing which leads to high stresses and subsequent failures initiated at grain boundary triple points. This effect occurs mainly at medium to low temperatures ( <0.4 Tm or <500°C).

It is important to note that when helium is present at boundaries and irradiation hardening is significant, (0.4 Tm < T< 0.5 Tm), the helium embrittlement and matrix hardening can combine to produce ductility losses more severe than the two processes acting alone. (26) Under such conditions, strain is concentrated at the grain boundaries which, because of helium embrittlement, are less able to withstand shear than before irradiation. These conditions result in grain boundary failure at much smaller strains than simple matrix hardening alone.

The temperatures in UWMAK-I have been limited to <500°C due to excessive lithium corrosion at higher temperatures. Thus, most of the ductility loss can be assumed to be due to matrix hardening and current fast reactor data can be used. Application of this data (24-27) to UWMAK-I conditions reveals that after one year of irradiation, the first few centimeters of the blanket will have reached the $0.5^{1/2}$ uniform elongation design limit. Unfortunately within the next year, the ductility of the first 20 cm of the blanket (the entire heat removal cell region) will fall below this limit. After 3 years, 30 cm of the blanket will have uniform elongation values less than 0.5%. The conclusion is that the heat removal cells (the first 20 cm of the UWMAK blanket) will have to be removed approximately every 2 years due to this radiation induced embrittlement. The recycling of these cells means almost 246,000 kg of radioactive solid waste will have be disposed of per year.

It must be emphasized that the above analysis does not take into account the possible synergistic effects of large helium concentration and displacement damage. We feel that inclusion of such effects would tend to reduce the wall lifetime to even lower values. Experimental information in this area is absolutely vital to the safe and economical operation of fusion reactors, regardless of the material of construction.

The swelling behavior of the blanket materials has also been analyzed in Reference 1. A design limit of 10% has been used although future reactor designs will have to be closely scrutinized for more precise limits. Both solution treated (ST) and 20% cold worked (CW) 316 SS was investigated. It was found that 20% cold worked 316 SS would undergo much less swelling than ST 316 SS during the 2 year first wall lifetime. The calculated values were 7.9% for ST 316 SS and 0.25% for CW 316 SS. However even 20% CW 316 SS swells as much as 10% at 500°C in 6 years of operation so that if the heat cells didn't have to be replaced because of embrittlement they would have to be replaced due to swelling.

The production of helium at the rate of 298 appm/yr and its subsequent collection into bubbles will cause less than 1% swelling in 2 years and less than 7% in 30 years. However, the effects of such high helium concentrations on the void swelling phenomenon are unknown. It is extremely important to assess the combined effect of high displacement damage ($>30$ dpa) and high helium contents ($>600$ appm) on the ductility of 316 SS at 300-650°C. Alloy development programs may have to be initiated to find more ductile but still readily available CTR structural materials if one wishes to construct economic CTR's.

The first wall of fusion reactors will be subjected to intense fluxes of both neutrons and high energy ions during operation, as shown in Reference 2. In UWMAK, the major contribution to the wall erosion rates is the sputtering caused by the 14 MeV neutrons. This effect accounts for 75% of the total wall erosion rate which is 0.22 mm/year. Other major mechanisms and their fractional importance are (D,T) sputtering (5%), self ion sputtering (10%) and back scattered neutron sputtering (10%). The erosion rates due to charged particle bombardment are calculated assuming the divertor is 90% efficient in collecting particles which diffuse out of the plasma before they strike the first wall. However, since the neutrons constitute $\sim 75\%$ of the wall erosion rate, the removal of the divertor would mean that the thinning rate would increase by only a factor of 3 or 4. Clearly, if no catastrophic self ion build up occurs, one could operate the first wall at this increased wall erosion rate for a few years. However, if we wish to limit the wall erosion due to particle bombardment to less than 1 mm (the maximum $\Delta \ell$ allowed by stress in 316 SS is $\sim 3.3$ mm including corrosion loss) then there is a 5 year limit at UWMAK-I operating conditions (using a 90% efficient divertor).

Transmutation effects on the properties of 316 SS appear to be minor provided the walls are changed every 2 years. A thirty year exposure would have the major effects of increasing the Mn content to $>6\%$, increasing the Ti to $\sim 0.2\%$ and the V to $\sim 0.9\%$ while reducing the Fe content from 62% to 58%, and Ni from 14% to 13%.

As a final point we have considered the effects of radiation damage on the superconducting magnets. This damage can manifest itself as a reduction in the critical current of the superconductor and as increased resistance of the copper stabilizer. We have found that radiation damage of the superconducting material (NbTi) does not appear to be serious over the lifetime of the plant. There will probalby be less than a 1°K drop in $T_c$ and $<2\%$ change in $J_c$ of the superconductor. Radiation in the form of neutrons and gamma rays does not appear to be a problem for the Mylar superinsulation in the magnets. The most severe problem for the superconducting magnets is the increase in resistivity for the Cu stabilizer. However, by increasing the Cu/Superconductor ratio and periodic annealing to room temperature, this problem can be solved. Therefore, in designing the shield for a system like UWMAK, it is the heat load in the magnet, and not radiation damage, which governs the design.

The major integral wall loading limitations for UWMAK-I are listed in table 2. They are expressed in terms of MW-years/$m^2$. This table shows that ductility will limit the first wall to 2MW-years/$m^2$ which, to a first approximation, could be obtained by a 2 year exposure to a 1 MW/$m^2$ wall loading or a 1 year exposure to a 2 MW/$m^2$ wall loading, etc. Table 2 also shows that the present limits of 10% swelling and 1 mm wall erosion place equally restrictive limits on the UWMAK-I first wall. Other radiation damage mechanisms are considerably less restrictive and are discussed in more detail in Reference 1.

Table 2

Major Radiation Damage Limitations for the UWMAK-I First Integral Neutron Wall

| Phenomena | Loading Limit [years] |
|---|---|
| Embrittlement<br>(uniform elongation > 0.5½) | 2 |
| Swelling ( > 10½) | 6 |
| Surface Erosion | 6 |

## 6. Blanket and Shield Design

One of the most difficult features of a toroidal reactor is the repair and maintenance of the fusion blanket. This statement automatically assumes that there will be random failure of the reactor components aside from the scheduled maintenance of the first wall. The UWMAK-I has been designed with the philosophy that the reactor should be segmented (12 modules in the present case) so that any substantial repair is done in hot cells outside the reactor itself. This approach is necessary because the radiation levels in the reactor after shutdown are in the neighborhood of several megarads. It also means that if spare segments are available, the down time of the reactor is only governed by the time it takes to remove and reinsert one module. An added feature is that malfunctions in the toroidal field coils could be repaired outside the reactor, something which would be very difficult to do in the inner part of the torus. A major disadvantage of this approach is that rather massive components (~several thousand metric tonnes) must be transported over distances of 100 meters to and from hot cell facilities. Considerable detail on how such an operation is to be performed in UWMAK can be found in Reference 1.

An important feature of the UWMAK-I design is the flow patterns of the lithium in and out of high magnetic field regions. (28) Since the pressure drop is proportional to $\overline{V} * \overline{B}$, it is obvious that both the magnitude and direction of the fluid can be utilized to reduce pumping losses. Large flow channels (~3-4 cm in diameter) are provided to reduce the velocity to ~4 cm/sec. The flow is also predominately perpendicular to the main toroidal field and the flow pattern is such that eddy current losses are minimized. The electrical pumping power required for all of the Li coolant is only 22 $MW_e$ or 1.5% of the plant output. This number should be compared to the total electrical auxiliary requirement of ~125 $Mw_e$ for UWMAK-I. Such an analysis shows that with proper care, liquid metals can be used economically in magnetically confined fusion reactors.

Perhaps one of the most severe limitations of the UWMAK system is the high corrosion rates between 316 SS and lithium at temperatures >500° C. (29) It has been found that as much as 1500-2500 kg of steel may be dissolved into the lithium per year. Such a large amount of corrosion product could represent a problem in the fouling of heat transfer surfaces, the deactivation of tritium extraction beds or the actual plugging of tubes in heat exchangers. Even more serious is the fact that a large amount (~10%) of the corrosion product will come from the first wall and therefore is highly radioactive. High radiation levels in loops outside the reactor may severely hamper normal maintenance. It must be noted that even those materials which exhibit good corrosion resistance may cause high radioactivity levels in the coolant. Such activity could come from neutron sputtering of the first wall into the coolant. It has been calculated, strictly on the basis of high 14 MeV sputtering yields (14), that this mechanism could contribute up to 50% as much radioactivity as chemical corrosion alone. This needs to be investigated experimentally.

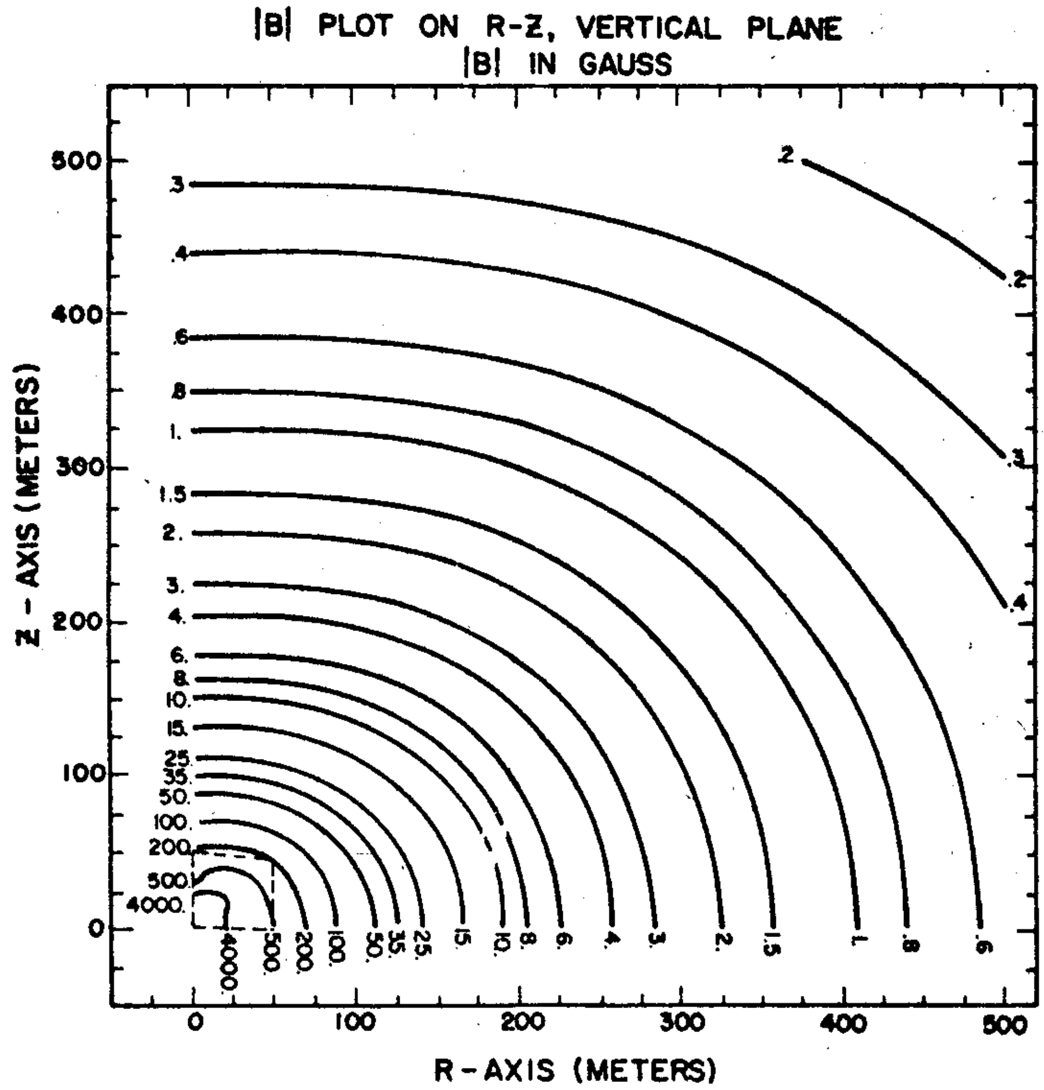
Finally, there is clearly room for ingenuity in the blanket and shield design. Clever assembly and disassembly schemes, methods of detecting leaks once they form, and mechanisms for shutting the reactor down quickly and safely are required.

## 7. Tritium

Tritium as a fuel for fusion reactors clearly implies that detailed consideration must be given to tritium handling, extraction, and expected leakage rates. Some tritium release is probably inevitable during operation of a fusion reactor and the principal escape routes in UWMAK are: permeation through the shield into the reactor hall; permeation into the helium cooling system of the magnet shield; permeation through headers and piping into the reactor hall and heat exchanger cells; leaks through any valves or joints; and permeation through the heat exchanger into the steam system. The escape route which appears most difficult to control is permeation through the heat exchangers into the steam system. Tritium recovery from the steam would be expensive but the leakage rate from the system will be small compared to the production rate. As reported in Reference 2, the tritium release rate from UWMAK would be 10.1 Ci/day and it is released almost entirely via the primary lithium coolant through the heat exchangers to the steam cycle. We would point out, however, that this 10.1 Ci/day would be diluted in 12000 gpm blowdown from the condenser and would be discharged into a large body of water. (30) The resulting tritium concentration is about $1.5 \times 10^{-4}$ $\mu Ci/cm^3$ or about 2% of the regulatory limit from 10 CFR 20 the plasma would result in a dose of $2 \times 10^{4}$ rem/week to a person obtaining a normal daily intake of water from this source.

The tritium production rate in UWMAK-I is 1.05 kg/day and the buildup of tritium in the lithium is 1.2 wt ppm/day. In contrast, tritium diffusing from the plasma at a rate of 7.4 kg/day is primarily collected by the lithium collectors of the divertor. Included with this tritium is about 5 kg/day of deuterium. The importance of this is that significantly more tritium must be handled by the divertor system than is bred in the primary coolant system. The steady state inventory of tritium in the primary lithium and extraction beds is 9.7 kg while the inventory associated with the divertor and its extraction beds is 3.8 kg. When one includes the tritium inventory in reserve, in the distillation system, and in the fueling system, the total inventory is about 30 kg. Therefore, even if the system did not use lithium cooling and did not breed tritium, the tritium inventory would be high, perhaps 15 to 20 kg.

Finally, the use of yttrium extraction beds (31) appears to be satisfactory based on thermodynamic considerations. The flow rate through the beds and the construction of the beds are reasonable. However, before such a system could be operated, it is necessary to verify the proposed equilibria at the temperatures of interest and to determine the effects of dissolved oxygen and nitrogen on the chemical reactions and the effects of corrosion products on the efficiency of such a system.



## 8. Radioactivity and Afterheat

The presence of 14 MeV neutrons as a principaled fusion reaction product implies that fusion reactors based on the D-T cycle will have a large amount of induced radioactivity and that an afterheat will be associated with this activity. However, the generation of radioactive isotopes is not a serious problem if they can be contained, have short half lives, and are not particularly harmful to man. In particular, the induced activity in the structural materials of fusion systems will constitute a solid, rather than a gaseous, waste and the low afterheat makes release of this activity to the environment highly improbable.

The radioactivity for UWMAK is characterized by a rapid buildup to levels of about $10^9$ Ci in less than 1 hour (regardless of the structural material, 316 SS, Nb - 1Zr, V-20Ti, or aluminum). This level is roughly maintained during operation. As reported in Reference 2 and elsewhere, (32) the decay of this activity is relatively slow, in 316 SS, dropping successively to $5 \times 10^8$ Ci in 2 years, $5 \times 10^6$ in 20 years, and $3.5 \times 10^2$ Ci in 200 years. The early time decay is governed primarily by $^{55}Fe$ ($t_{1/2} = 2.7$ years). The impact of these results is that remote maintenance and handling will be required even after modules of the reactor are removed for servicing or other purposes. Also, since radiation induced embrittlement limits first wall life to about 2 years, one is faced with removal of an average of 246,000 kg per year of solid radioactive waste. Compaction and on-site storage appears to be feasible since the afterheat is relatively low, namely, $29 MW_t$ at shutdown after 2 years of operation. Vogelsang et. al. (32) have also compared fusion with advanced fission systems (33) on the basis of Biological Hazard Potential (BHP). They conclude that a fusion system such as UWMAK-I will have overall BHP indices that are a factor of 100 to 1000 lower than an advanced fission system. Thus, it appears that fusion systems like UWMAK can offer a real advantage in terms of radioactivity and afterheat, compared with advanced fission reactors.

The total afterheat at shutdown in the 316 SS blanket is $29 MW_{th}$ after 2 years of operation and 33 megawatts after 30 years. Almost 50% of this afterheat is generated with the heat removal cells and this drops by a factor of 30 in 20 years. The maximum rate of temperature increase in a loss of flow accident was calculated to be $0.1\,^{\circ}C\ sec^{-1}$ but it appears to be more like $0.01^{\circ}C\ sec^{-1}$ when convection and conduction forms of heat loss are considered. It is concluded that afterheat represents no serious problem even in the event of a loss of flow accident in UWMAK-I, whether or not the plasma remains on or is quenched. However, a loss of coolant accident without plasma quench can cause more rapid first wall temperature increases. This is being investigated. A detailed analysis of the loss of coolant accident with the plasma operation should be made to insure that major damage will not occur in the CTR blanket.

The total afterheat in UWMAK-I after shutdown and 10 years of operation is not particularly sensitive to

Table 3

**Resource Requirements and Availability Metric Megatons-Based Year 2000**

| | | U.S. Reserves | | ex-U.S. Reserves | |
|---|---|---|---|---|---|
| Metal | Requirement For $10^6$ MWe | At Present Prices | At 3x | At Present Prices | At 3x |
| Fe | 15 | 8500 | $\geq 10^5$ | $170 \times 10^3$ | Large |
| Ni | 1.5 | .14 | 14.4 | 24 | 922 |
| Cr | 1.9 | 0 | 1.2 | 370 | 890 |
| Li | 0.95 | .8 | 2.7 | .2 | .2 |
| Cu | 3.25 | 20 | > 100 | > 100 | 320 |
| Pb | 11.0 | 35 | > 100 | 50 | > 500 |
| Be | .12 | .018 | .018 | ? | .03 |

blanket material. The value at shutdown varies from 0.55% to 0.1% of the operating power for the three metals studied here (316 SS, V-20Ti, Nb-1Zr). However, the afterheating V-20Ti decays faster than the steel and Nb alloy and is at half the shutdown level after a month of decay.

From such considerations, it is also concluded that methods should be developed to collect, store and ship several metric tonnes per year of radioactive corrosion products from the stainless steel. Also more detailed calculations are required on the radioactivity levels at various maintenance points outside the reactor due to the deposition of 316 SS corrosion products. Finally, long term solutions to the concentration and storage of spent reactor components must be addressed. In particular, methods of handling ~250 metric tonnes of 316 SS heat removag cells per year should be studied. On - site storage may be feasible but central burial facilities should be investigated.

## 9. Resources

A preliminary assessment of the availability of certain metals that appear important to a fusion power industry based on UWMAK type reactors has been made. (34) The results are summarized in Table 3. We have purposely divided the reserve estimates into U.S. and external to U.S. since self-reliability in a commodity as basic as electricity has become rather crucial. The conclusion is that for a UWMAK type system, the U.S. reserves of Ni, Cr, and Li are less than would be required for a $10^6$ MWe economy ( 1/3 the projected electrical generation capacity in the year 2020) and that lead is only about three times the requirement. It is important to note that the lithium reserves in a system where lithium is used as a coolant do not greatly exceed the than half the cost of reactor materials is in fabrication and assembly. Therefore it may be possible to use materials which cost as much as three times present requirement. However, if lithium is only used for breeding, the reserves far exceed the requirement. At three times present prices, all metals except Cr exceed the requirement for a $10^6$ MWe economy. Since the reactor itself only constitutes ~1/3 of the total plant cost, a price increase of 3 times the present value only contributes ~70% to the cost of electricity from fusion. This percentage is further reduced by the fact that more prices and still not increase the cost of electricity by more than 35%. The use of beryllium has been frequently discussed as a means for improving energy production in fusion systems. However, given the very low reserves of Be in the context of the requirements of a $10^6$ MWe economy, the use of large amounts of Be either in solid form in UWMAK or in FLIBE does not appear to be practical.

## 10. Summary

We have presented in this paper a discussion of the major conclusion of the UWMAK-I conceptual design (1) and treated in some detail the implications of these results. Overall, most of the technological problems posed by Tokamak fusion reactors appear to be solvable within reasonable extensions of existing technology. The two general problem areas which cannot be categorized this way and which have large remaining undertainties relate to materials, particularly first wall problems, and plasma physics and plasma technology, including scaling, impurity control and fueling. A list of problem areas is given in Table 4 which fall in these two general categories. We would conclude therefore, that while many of the identified technological problems appear solvable, major advances are required in the state of plasma physics and certain reactor technology problems before a reactor such as UWMAK-I could be built.

Table 4

**Areas Within Extendable Technology**

- Multi-Ampere, Megawatt Neutral beams
- Lithium-Stainless Steel Systems
- Tritium Breeding, Extraction and Leakage
- Modular Design; System Disassembly
- Large NbTi S/C Magnets
- Energy Storage and Transfer
- Afterheat and Radioactivity
- Power Cycle

**Areas With large Uncertainties**

- Plasma Startup and Scaling
- Impurity Control, Divertors
- Fueling, Long Burn Times

- Large Nb3Sn S/C Magnets
- Unstable magnets

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# Applications of Fusion Power Technology to the Chemical Industry

**Morris Beller, James R. Powell, and Meyer Steinberg**

Controlled Thermonuclear Reactors (CTR) offer the potential of large, low-cost energy inputs for chemical production. Energy forms which can be derived or obtained directly from CTR's are ultra-violet (UV), hot ionized plasmas, high-energy neutrons, high temperature fluids, X and gamma radiation, and electricity. Some of these energy forms may offer unique capabilities in terms of utilization, efficiency, intensity, and cost which are presently unobtainable for the chemical and materials processing industries.

## CTR Energy Forms and Utilization

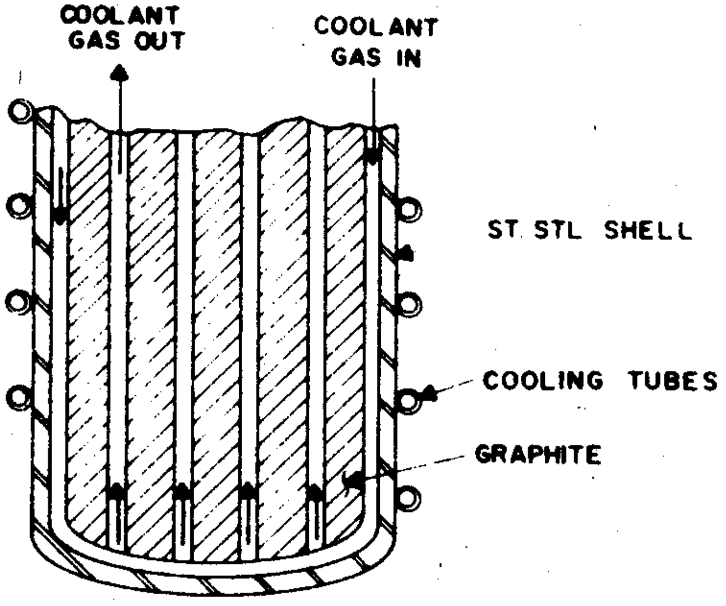
### Thermal Energy

An individual module is shown in Fig. 1. It consists of a stainless steel shell wound with stainless steel tubes for water or helium coolant protection of the shell. Inside the shell, a drilled graphite core permits inlet gas to enter peripherally, remove heat and exit through the holes in the core. Suitable headers to supply the modules and to direct the exit gases out are required. This type of design probably does not permit a breeding ratio of 1.0, thus some tritium would be required from other reactors for the system. It is estimated that temperatures up to 1500° could be attained in the process gas with this design. There is some question as to the ability to use the graphite core for heating air. This problem could probably be circumvented by using a metallic oxide in place of the graphite.

The direct heating design permits gas-phase chemical reactions to occur in the blanket, or high temperature process gas heating for subsequent use outside the CTR. In either case, the coolant gas employed must be compatible with the module materials employed. The water coolant from the module coils can be expanded in

### Table 1
### CTR Energy Forms for Chemical and Material Processing

| Energy | Intensity | Pressure | Available fraction from D-T |
|---|---|---|---|
| I. Thermal | | | |
| A. Blanket | | | |
| Direct Coolant | 1500°c | 30 atm. | 0.75 |
| Indirect He Coolant | 2500°c | 30 atm. | 0.75 |
| B. CTR Plasma | >3000°c | low | <0.10 |
| II. Electrical | | | |
| A. Low voltage electrochemical | to 10V | – | 0.40 |
| B. High voltage arc & discharge | to 50kV | – | 0.40 |
| III. High Energy Radiation | | | |
| A. Neutrons | to 14.1MaV | 200 atm. | 0.80 |
| B. Gamma — direct & indirect | to 10MeV | 200 atm. | 0.58 |
| C. Secondary particles p, $\alpha$ $\beta$ | 2MeV | 100 atm. | 0.04 |
| D. Ionized particle from plasma | 10keV | 100 atm. | 0.10 |
| IV. UV from plasma | 5-20eV | 1-10 atm. | 0.10 |



BLANKET MODULE
FOR
DIRECT THERMAL PROCESS HEATING

Figure 1

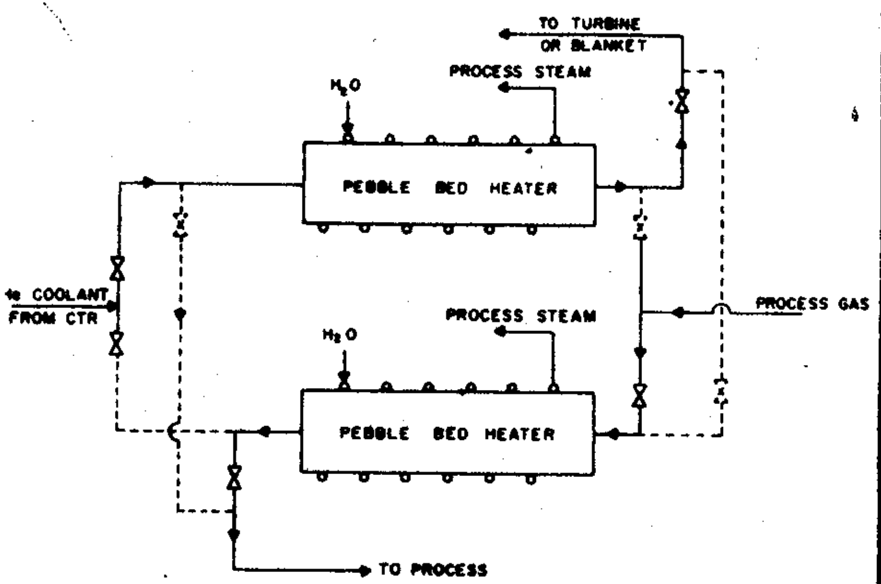


Figure 2 THERMAL PROCESS
REVERSING HEAT EXCHANGER CYCLE FOR INDIRECT HEATING

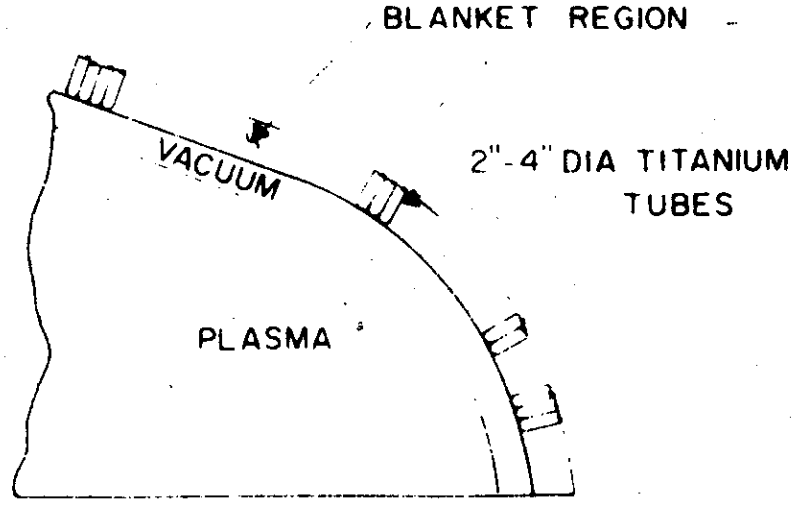
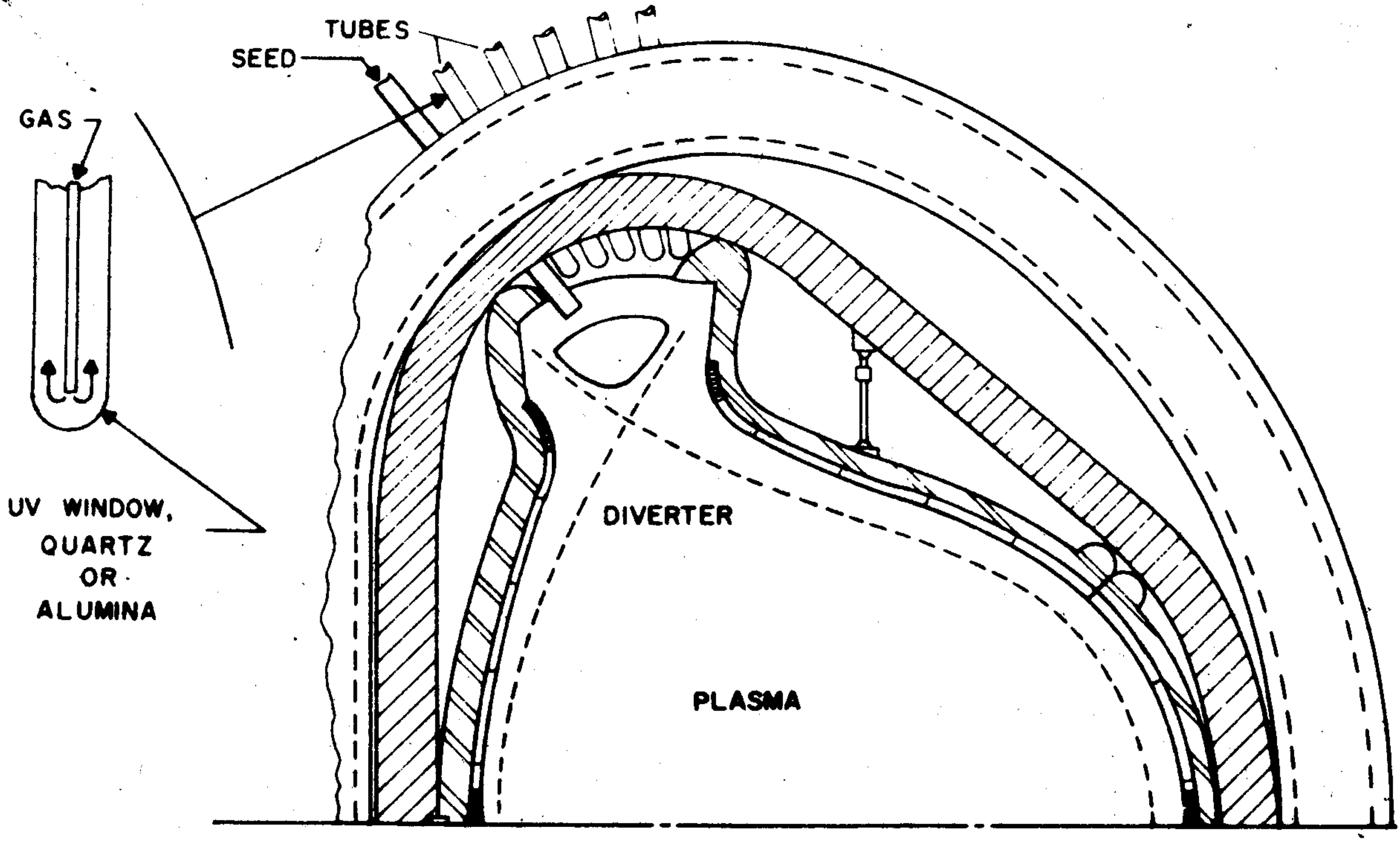


Figure 3

NEUTRON-GAMMA
RADIATION PROCESS CTR



UV PROCESS CTR Figure 4

a conventional turbine to produce electricity for auxiliary plant use, or used directly as process steam in other parts of the plant.

Temperatures above 1500°C, if required, could be attained by utilizing helium coolant from the blanket in a regenerated pebble-bed arrangement, shown in Fig. 2. Two pebble-bed heaters are employed for the process. By a suitable valve configuration, hot helium passes through the first vessel to heat the bed. As the He is cooled in passing through the bed, it can be returned to the blanket for further heating or passed through a turbine to generate power. When the bed has reached the desired temperature, the valves are switched to pass the He through the second bed. Process gas is then passed back through the first hot bed and heated to the temperature required. When the bed cools to the minimum temperature allowable, the procedure is again reversed.

## Table 2
## Thermal Energy Requirements from CTR

| Chemical | Production, $10^6$ Tons<br>Present | <br>2000 | Fusion Energy[(1)] Consumption, MW (t), 2000 |
|---|---|---|---|
| Cement | 80 | 320 | 120,000 |
| H-Iron | 85 | 130-174 | 182,000-244,000 |
| Chlorine | 10.3 | 26-44 | 50,000-85,000 |
| Oxygen | 16 | 39-75 | 6,000-11,700 |
| Ammonia (Anh.) | 16.2 | 28-51 | 80,000-150,000 |
| Hydrogen | 5.2 | 19-104 | 242,000-1,296,000 |
| TiO2 | 0.8 | 1.8-3.9 | – |
| Phosphoric Acid | 6.8 | 24 | 35,000 |
| Acetylene | 0.5 | 0.5 | 2,000 |
| Sodium Silicate | 0.7 | 2.8 | 600 |
| Lime | 19.7 | 80 | 18,000 |
| NaOH | 10.6 | 31 | See Chlorine |
| Gypsium | 8.6 | 21-31 | 500-1,700 |
| Methanol | 3.5 | 14 | 33,000 |
| Aluminum | 5.0 | 22-44 | 110,000-220,000 |
| | | Total | $1.3\text{-}2.1 \times 10^6$ MW (t) |

(1) Taken at 75% Energy Recovery for Thermal Reactions, 40% Conversion for Electricl Use, 0.6 Plant Factor

To prevent process gas from mixing with the He between cycles, a purge is required at every cycle change before He is admitted. This could be done with He gas to sweep out residual process gas. The He can be removed by partial condensation processes. The process gas would have some He mixed with it as a result of using the indirect heating cycle. This could also be recovered if desired. Use of this cycle would require a highly optimized design to achieve efficient heat recovery, and to minimize He losses.

A detailed discussion of the technical aspects of electrical energy utilization from CTR power sources does not appear warranted. The technology for its application will not be different regardless of the source of electric power. Philosophically, however, there are major implications involved. The major inference to be drawn is that fossil fuel is not required for generation. Additionally, the higher efficiency of generation, compared to present-day fossil-fueled or nuclear fission plants and the low fuel cost hsould permit low-cost power. This would mean that processes which shift in technology as a function of power cost would benefit economically from a CTR technology. Electric power from CTR can be utilized for the same low or high voltage applications presently employed and may offer economies in chemical processes sensitive to power cost.

### High Energy Radiation

The use of radiation to initiate chemical reactions has been studied for many years. In general, radiation is of interest for endothermic reactions. Lind (1) and Steinberg (2) have reviewed the chemistry and technology of radiation applications. Although radiation is used industrially for some chemical processes, such as ethyl bromide production and crosslinking of polyethlene, it is now widely used because of problems such as radioactive product contamination, shielding requirements, and generally poor economics because of low product yields for many reactions. The major hinderance to using fission reactor energy directly has been the contamination problem. The CTR does not have this shortcoming, and therefore is of interest as a potentially large radiation source for chemical reactions. Fig. 3 shows an arrangement for gas-phase chemical reactions in a CTR blanket. Titanium tubes are used for recirculation of the process gas in the reactor to allow product buildup, and temperature is controlled by the

## Table 3
## Unit Energy Requirements Present Processes

| Chemical | Process | Energy Consumed<br>BTU/Ton | <br>kWh/Ton |
|---|---|---|---|
| Cement | Calcining | $7 \times 10^6$ | |
| H-Iron | Ore Reduction | $13.7 \times 10^6$ | |
| Chlorine | Electrolysis | $22 \times 10^6$ + | $2.8 \times 10^3$ |
| Oxygen | Air Separation | | 400 |
| Ammonia | Nat. Gas Reforming | $34 \times 10^6$ | |
| Hydrogen | Electrolysis | | $36 \times 10^3$ |
| Phosphoric Acid | Electric Furnace | | $4 \times 10^3$ |
| Acetylene | Nat. Gas-Oxidation | $190 \times 10^6$ + | $1.5 \times 10^3$ |
| Sodium Silicate | Furnace | $5 \times 10^6$ | |
| Lime | Calcining | $5 \times 10^6$ | |
| NaOH | Electrolysis | See Chlorine | |
| Gypsum | Calcining | $0.4 \times 10^6$ | |
| Methanol | Nat. Gas Reforming | $18 \times 10^6$ | |

gas flowrate. The energy of the neutrons is converted to gamma energy by inelastic scattering, and a fraction of the gamma energy plus that of the remaining neutrons is deposited in the reactant gases. Reactions of interest using radiation are nitrogen fixation from nitrogen-oxygen mixtures, formation of ozone from oxygen, and carbon monoxide production from carbon dioxide.

## Plasma Energy and UV

The use of plasmas for various materials processing applications has been discussed by Eastland and Gough (3); their concept involves transference of the plasma to a region where various materials can be converted to their elemental forms. Additionally, by the proper choice of seed materials, the plasma energy can be converted to radiative energy, such as ultra-violet (UV).

A radiation system is illustrated in Fig. 4. Seed is injected into the plasma divertor to produce UV. Process gas is exposed to the radiation through appropriate windows, in the form of tubes, for conversion to other chemical species.

## Table 4
## Electrical Energy Requirements from CTR

| Chemical | MW (e), 2000 |
|---|---|
| H-Iron | 45,000-61,000 |
| Chlorine | 10,000-17,000 |
| Oxygen | 2,400-4,700 |
| Ammonia | 28,000-51,000 |
| Hydrogen | 97,000-518,000 |
| Phosphoric Acid | 14,000 |
| Acetylene | 800 |
| Sodium Hydroxide | See Chlorine |
| Methanol | 13,000 |
| Aluminum | 44,000-88,000 |
| Total | 254,000-767,500 |

In a D-T reactor, only 20% of ther energy is available in the plasma; assuming 50% efficiency for conversion to UV and deposition in the chemical reactant, 10% remains to carry out chemical conversion. In a D-$^3$He reactor, by importing $^3$He from other reactors all the plasma energy can be made available for conversion to radiative energy. If $^3$He is not imported, approximately 55% of the energy is available *in situ*. The remaining energy can be used for other purposes, such as power generation or thermal applications.

## Potential Processes for Application of Fusion Energy

A study was made of the chemical and realted processing industries to determine where CTR technology can make significant contributions in the areas of energy utilitzation efficiency and fossil fuel substitution. Table 2 presents a summary of high volume, energy intensive products with their production rates in the present time frame (4,5). Projections for the year 2000 are also listed (6). The unit energy requirement per ton of product is shown in Table 3, specified as electrical or thermal energy. Fusion energy was calculated based on the projected year 2000 production. The energy projection assumes the entire production rate is met by CTR energy. Energy output is based on 75% heat recovery for thermal reactions. 40% conversion for electrical use and a 0.8 plant factor. Obviously, the assumption that the entire production of these materials utilizes CTR energy is extremely optimistic, but it is also apparent that the potential energy required to satisfy even a minor fraction of the demand can still be enormous.

Table 4 outlines the projected electrical demands of materials which can utilize electrical energy in their production. It should be noted that the thermal energy required to generate the electricity was included in Table 2. In some cases, such as H-Iron, ammonia, and methanol, it is assumed that the hydrogen required is generated by water electrolysis. The hydrogen in these cases has not been included in the separate hydrogen category, which is slated to meet other needs such as coal gasification, petroleum refining, and general chemical applications.

Table 5 lists processes and products which are of interest for the potential application of fusion energy. A brief description of each follows, outlining present or past production methods, with an indication of the role fusion energy sources may play in their future production.

## Thermal Reactions

### 1. Wisconsin Process for NO (7)

This process employed a gas-heated pebble furnace for the thermal reaction of air to form NO at 2100°C. The yield was about 2% NO by volume at 1% thermal efficiency. The use of the indirect thermal reaction method with fusion energy appears directly applicable to this process.

### 2. Acetylene from Methane (8)

Acetylene production has not kept pace with the growth of the chemical industry because of increased reliance on petrochemical feedstocks for raw materials. Although acetylene was produced primarily from calcium carbide in the past, increasing power costs brought about a change to the use of hydrocarbons, typified by natural

## Table 5
## Potential Processes for Application of Fusion Energy

**Thermal Reactions**

1. Wisconsin Process for NO
2. Acetylene from Methane
3. Decomposition of $CO_2$ to CO and $O_2$
4. Decomposition of Water
5. Coal Gasification
6. Shale Retorting
7. Lime
8. Cement
9. Gypsum
10. Iron Ore Reduction
11. Ammonia
12. Titanium Dioxide
13. Sodium Silicate

**Electrical Processes**

Electrochemical

1. Hydrogen and Synthetic Fuels
2. Oxygen
3. Caustic-Chlorine
4. Metal Refining — Al, Mg, Cu

**High Voltage Electrical**

1. Phosphorous — Phosphoric Acid
2. Birkland-Eyde, $NO_2$
3. Acetylene via Arc Process
4. Hydrogen Peroxide
5. Ozone

**Radiation Processes**

1. H ? Decomposition
2. $N_2$ Fixation
3. $CO_2$ Decomposition
4. Ozone Synthesis

gas. the major process is the use of partial oxidation of methane:

$$CH_4 - 2O_2 \rightarrow CO_2 - H^2O \quad (1)$$

$$2CH_4 \rightarrow C_2H_2 - 3H_2 \quad (2)$$

Step (l) provides the heat to thermally crack methane to acetylene in step (2) at 1550°C. It is apparent that a high-temperature gas stream fron a CTR might be useful as a heat source for the reaction.

### 3. Decomposition of $CO_2$ to CO and $O_2$

$CO_2$ is a waste product from many chemical processes which is normally vented to the atmosphere. It could serve as a carbon source by conversion to CO, which is useful as a component of synthesis gas when combined with hydrogen. CO can also be used to generate $H_2$ via the water gas reaction, or to synthesize methanol. An interesting, novel method of CO generation which is presently not utilized is by direct thermal deconppsition of $CO_2$. It can be calculated thermodynamically that at 2200°C a 7% yield of CO can be achieved. A major problem in this scheme is the separation of CO from $O_2$.

### 4. Decomposition of Water

Processes for the decomposition of water to produce hydrogen directly have been pursued for many years. Although the electrolysis of water is well-known technologically, it does not compete with hydrogen generation from natural gas in the near term. In the far term, multistep chemical cycles in which the reactants are regenerated, and the net result of which is the decomposition of water, are interesting since they require an external heat source to supply the reaction energies. Extensive work on these cycles has been conducted at Euratom (9). Should either the overall efficiency or the economics of these systems warrant commercial application, fusion reactors would certainly be of interest for application to this technology.

### 5. Coal Gasification (10)

Coal gasification is a process in which steam reacts endothermically with carbon to produce a gas mixture which can be used for fuel. Actually, a complex series of reactions occurs in the combustion zone of the coal gasifier, which is a refractory-lined, water-cooled vessel. Steam and air are introduced at the bottom, coal at the top. The overall reaction is endothermic. The resultant gas is called low BTU gas, heating value of about 175 BTU per cu. ft. Although a waste heat boiler is utilized to raise steam from the hot exit gases, reducing their temperature from 510°C to 290°C, there is still a 40% steam deficit in the overall balance which would be supplied from a CTR. The ratio of additonal steam required is about 0.32 lb per lb of coal consumed.

### 6. Shale Retorting (11)

The process of shale oil recovery has a retorting enthalpy requirement of 300 BTU per lb at 475 C. The process envisioned, and presently under field test, employs a preheated ceramic pebble bed system for pyrolysis. The pyrolysis vapors are later condensed and fractionated. The indirect pebble-bed system previously described for employing CTR thermal energy appears directly applicable to the shale oil retorting process.

### 7. Lime (8)

Lime is produced from limestone directly by calcining to remove $CO_2$. One ton of lime requires five million BTU from coal or gas for the decomposition, which occurs above 900 C. The application of CTR thermal energy to this process is of obvious value.

### 8. Cement (12)

Cement is obtained by calcining a mixture of clay and limestone or similar materials. There are many commercial variations, but the processes are similar despite some differences in the raw materials or their proportions. The reactions of dehydration and decarbonization which take place are both endothermic, although the clinker formation is exothermic. The net heat requirement has been estimated as about 900 BTU/1lb., but the actual fuel used indicates a requirement about four times greater. The technology necessary to adapt the CTR as an energy source for this process would be identical to that required for calcining lime.

### 9. Gypsum (8)

Calcium sulfate (gypsum) is manufactured by calcining gypsum rock to remove three-fourths of the water of crystallization. A calciner is used in a vertical configuration, and the process is completed when the mass reaches 160°C. The use of low-level heat from CTR steam or coolant to heat air for the calcining operation appears to be a simple technological adaptation.

### 10. Iron Ore Reduction

The direct reduction of iron ores has been extensively reviewed by Brown (13). He has defined direct reduction of iron oxides to iron as any process "which is carried out in equipment other than the blast furnace." The reducing agents generally used are carbon, carbon monoxide, hydrogen, or mixtures of these.

The H-Iron process has been widely publicized and extensively researched. It was the first commercial process to use a fluidized solids technique. The process operates at about 540°C, 500 psia, and employs almost pure hydrogen as the reductant. The reduction takes place in three staged beds within the reducing vessel, employing -10 mesh ore moving downward countercurrent to a pre-heated hydrogen stream at 540°C. The reduced charge, of essentially the same size as the feed, is removed from the bottom of the vessel.

The hydrogen requirement is approximately 22,000 scf per ton of iron produced. Approximately one-third of the reaction heat required is supplied by the hydrogen reacting with the ore, and the additional energy to maintain the process is obtained from hydrogen preheating.

The energy for hydrogen preheating is obtainable by heat exchange with CTR coolant. The hydrogen required is available from electrolysis of water from CTR electric power, or through decomposition of $CO_2$ (radiolytic or thermal) in the CTR with subsequent water gas shifting, or by water-splitting cycles.

### 11. Ammonia (8)

Ammonia is produced by reforming natural gas with steam to produce carbon monoxide and hydrogen.

$$CH_4 + H_2O \rightarrow CO + 3H_2 \qquad (3)$$

The carbon monoxide reacts further with additional steam to produce more hydrogen.

$$CO + H_2O \rightarrow CO_2 + H_2 \qquad (4)$$

During the course of reaction (3), sufficient air is added to bring the nitrogen concentration to that required for the final synthesis of ammonia, which follows steps for the removal of carbon dioxide and residual carbon monoxide.

$$3H_2 + N_2 \rightarrow 2NH_3 \qquad (5)$$

The necessary hydrogen may be generated by the processes previously described. The additional heat required for the steam reforming step is available by direct heating of the required air in the CTR blanket module array.

### 12. Titanium Dioxide (8)

Rutile titanium dioxide is made by chlorinating rutile ore, and oxidizing the resulting titanium chloride vapors to titanium oxide in a burner supplied with air.

The burner is the key to the process, providing for very rapid heating of the reacting gases to about 1300°C, the temperature at which rutile crystals form. The CTR may provide the thermal energy necessary for the oxidation step.

### 13. Sodium Silicate (8)

Sodium silicate is produced by the fusion of silica and sodium carbonate in a regenerative furnace at 1200°-1400 C. Fuel gas (natural or producer gas) and air are used to maintain the necessary temperature. The substitution of air heated in a CTR blanket module array may be considered for this purpose.

## Electrical Processes

The application of potential low-cost power from any source is of obvious interest to the chemistry industry. CTR technology offers this potential, and if it can be fulfilled, it is then also obvious that the chemical industry will utilize it. This is particularly true for products which can be produced by an alternate methods; the process choice is dictated by the power cost. A typical example is phosphoric acid, which is produced primarily by either the electric furnace method or the wet process; the choice is strongly affected by power cost.

A discussion of large power-consuming chemical processes is described in the following section, with appropriate implications about their role in an economy based on CTR technology.

## Electrochemical

### 1. Hydrogen and Synthetic Fuels

The prospect of large blocks of off-peak, low cost power from CTR makes hydrogen attractive as a potential fuel or fuel component. It can be readily generated by electrolysis of water. The theorectical power consumption is 14.9 kWh per lb H (9), but practical cells are assumed to require about 18 kWh per lb.

Hydrogen can be used directly in slightly modified internal combustion engines. For practical application in this area, a considerable problem is the carrying capacity of a vehicle because of the low density of either the gas or the liquid. The use of hydrides (14) is possible, but these materials impose a weight penalty.

Another possibility is to use the generated hydrogen to produce methanol by reaction with carbon monoxide or carbon dioxide. The resultant liquid can be used in conventional vehicles (also slightly modified). Although methanol provides only half the energy obtainable from gasoline on a volume basis, its handling properties and ease of use make it a stong contender for automotive use. It should be noted that the projected production of methanol in Table 2 does not include any provision for methanol as a motor fuel. If, by the year 2000, 50% of the projected energy demand for transportation alone was met by methanol, the production required would increase by two orders of magnitude above the value given. Enormous quantitites of power would be required to produce the necessary hydrogen, implying a concommitant increase in CTR capacity.

### 2. Oxygen

Oxygen is presently produced by low-temperature air separation. The process requires about four hundred kWh per ton of oxygen for compression, thus the cost is strongly a function of power costs. If hydrogen from electrolysis becomes viable, great amounts of by-product oxygen will be available. In any case, a CTR economy producing power, hydrogen or both will benefit large users of oxygen.

### 3. Caustic-Chlorine (15)

Chlorine and caustic soda are produced from the electrolysis of brine; average energy consumption is about 2800 kWh per ton of chlorine. A major problem in the industry is imbalance between supply and demand for the two products. Chlorine demand has been historically rising at a greater rate than caustic demand. In addition, caustic demand fluctuates more than does that for chlorine. For these reasons, other processes which do not produce caustic are of interest. Among these are the electrolysis of hydrochloric acid and the partial oxidation of hydrochloric acid. An added incentive for the greater use of such processes is the environmental problem of excess hydrochloric acid disposal. By-product oxygen available from hydrogen electrolysis cells might strongly affect the process choice.

### 4. Metal Refining

Many metals are refined by electrical processes. Among these are aluminum, magnesium, and copper. Aluminum is a particularly large energy consumer, requiring 14,000 kWh per ton for its production. Electric furnace steel production is also expanding; should H-Iron production become feasible on a large scale, electric furnace expansion, and thus power requirements, would become enormous.

## High Voltage Electrical

### 1. Phosphorous-Phosphoric Acid (8)

A primary method of phosphorous production is by electric furnace reduction of phosphate rock with coke to elemental phosphorous. Subsequent oxidation by air to phosphorous pentoxide followed by hydration yields phosphoric acid. The implication of CTR power for this method as opposed to the wet process, which produces phosphoric acid directly, has been discussed previously Some advantages of the furnace process are:

a. It produces phosphorous directly; this can be shipped to distribution areas cheaper than the acid. The phophorous is then easily converted to the acid for distribution.

b. The wet process has some serious enviromental problems, among which are disposal of calcium sulfate waste, and fluorine dispersal into the air or streams.

### 2. Birkeland-Eyde, $NO_2$ (16)

The first process for fixation of atmospheric nitrogen employed an air-current blown through an electric arc at 3000°C. Some nitrogen and oxygen in the air combined to form nitric oxide, and a rapid quench to 600°C caused further reaction with oxygen to produce nitrogen dioxide. This process is primarily of historic importance, although at one time it was in commercial use.

### 3. Acetylene via Arc Process (8)

Several processes for acetylene manufacture employ hydrocarbon cracking in an electric arc. A high flux density keeps reaction time at a minimum, In the U.S., du Pont is the only company employing an arc process. The cracked gas is rapidly quenched in two steps with liquid propane and water. Power consumption is 5.6 kWh per lb of acetylene, and the acetylene yiedl is 100 lb per 120 lb of methane and 40 lb propane. This is about twice the power consumption of the calcium carbide-acetylene route.

### 4. Hydrogen Peroxide (8)

Hydrogen peroxide can be produced by electrolysis of ammonium bisulfate to produce ammonium persulfate. Outside the cell, the persulfate is hydrolized by steam to hydrogen peroxide and ammonium bisulfate, which is recycled. The electrical power requirement is 5700 kWh per ton of hydrogen peroxide. The electrolysis method is being replaced by organic auto-oxidation processes which employ hydrogen and oxygen. Whichever method is eventually used, power will be required either directly for electrolysis of bisulfate or indirectly for oxygen and hydrogen production.

### 5. Ozone

Ozone is prepared commercially by the reaction of an oxygen-containing feed gas in an electric discharge. Another technique employs ultraviolet energy, but at present this method produces low volume and low concentration ozone.

Commercial ozone generators (ozonizers) generally consume 3.75-5.0 kWh per lb ozone generated from a pure oxygen feed. If air is the feed gas, power consumption is doubled.

Ozone is widely used in Europe for drinking water treatment, as opposed to chlorine which is used in the U.S. Chlorine is known to react woth components of water, such as phenols and amines, to produce distasteful and toxic organic chlorides. Ozone, on the other hand, is an extremely powerful oxidant which can decompose many organic compounds. As a result, there has always been interest in using ozone to replace chlorine for water treatment.

## Radiation Processes

### 1. Water Decomposition

The production of hydrogen from the photolysis of water has been proposed (17), using a plasma seeded with aluminum to produce 1800-1950 UV radiation. It is doubtful if this process can approach the efficiency of water electrolysis for this purpose, even with a dual cycle system which produces hydrogen and uses waste heat to generate power. The energetics of competing processes for water decomposition were examined by Fish and Axtmann (18), who concluded that electrolysis efficiency will be difficult to exceed.

### 2. Nitrogen Fixation

Nitrogen and oxygen combine under neutron and gamma radiation to form $NO_2$. This reaction occurs in low yield. It is necessary to use a dual cycle system which also produces power for hydrogen electrolysis, leading to ammonia, to make the economics competitive with those obtained from natural gas (19).

### 3. Carbon Dioxide Decomposition

The radiolysis of carbon dioxide to produce carbon monoxide using neutron and/or gamma energy has been reported (2). Carbon dioxide is available as a by-product from many industrial processes. It has also been proposed that it be extracted from the atmosphere (20,21) for direct combination with electrolytic hydrogen to produce liquid fuels such as methanol.

### 4. Ozone Synthesis

Ozone can be produced by the neutron of gamma irradiation of oxygen (22), or by the use of seeded CTR plasma for ozone synthesis via UV photolysis. Theorectically, both methods offer higher yields than the electrical discharge method. Ozone has also been synthesized in a helium plasma jet (23) at efficiencies exceeding those obtained in commercial ozoners.

## Summary and Conclusions

This overview has pointed up a large number of energy intensive, high volume chemicals to which various energy forms from CTR may be applied. The present energy situation indicates that even if fossil fuel supplies are available, the rising cost of these fuels lead to closer comparisons with alternative non-fossil energy forms.

Obviously, electric power from CTR will be utilized in those processes which are dependent on this energy form, but it may also be used in other processes which previously used other energy sources. This can be done either directly, or indirectly via hydrogen or liquid fuels derived from CTR power.

Thermal energy from CTR is readily adaptable to processes using moderate temperatures with very little technological change. Processes requiring heat in the 1000-1500° C range will require some extensive engineering development; however, no barriers appear to exist which will impede these adaptations.

Radiation processes require some new advances in technology. Although some of these processes offer yields higher than existing conventional processes, energy deposition efficiencies must be improved, and more work is required on rapid quench techniques to stabilize desired chemical species.

An interesting speculation arises concerning the interplay between chemical processes and CTR. It may not be desirable to use a CTR to generate one specific chemical product, but it may be feasible to generate an entire range of products. This possibility arises through considerations of raw material sources, distance to market for finished materials, energy requirements, and enviromental problems. The situation may lead to the evolution of CTR "parks," where by-products from one process may become raw materials for others. As example by-product HCl from chlorinated hydrocarbon processes could be converted to chlorine by partial oxidation using oxygen from hydrogen electrolysis cells. Thus, the HCl which is considered a pollutant from some processes becomes a significant chlorine source. Another example is $CO_2$ from calcinating operations, which is often vented. Combined with hydrogen, methanol can be produced for use as a fuel organic intermediate.

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# Project Jericho — An All Out Assault on Controlled Fusion

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WASHINGTON, D.C. — America's future very much depends upon the resolution of the energy picture. The press and the media have created the impression that the energy crisis is behind us, when, in fact, the day of reckoning has been postponed. Our nation must come to grips with the energy problem and we cannot afford to delay much longer, particularly in the achievement of controlled thermonuclear fusion. The danger continues to persist that the pressures to build up the energy supplies will result in the proliferation of fission reactors, an awesome threat to human safety, especially in the form of the fast breeder (reactor) and its environmental hazards.

Project Jericho has been proposed as a revitalized approach to pursue certain aspects of fusion beyond the realm of the old Sherwood Project and even the more recent laser heating of pellets. It appears that there are political obstacles to entering an unencumbered phase of thermonuclear research and development. A fresh spirit is needed to overcome prejudices that exist in entertaining fruitless ideas that have remained unrewarding even after the passage of more than two decades; by this time is it not natural to inquire whether the original idea of magnetic containment — the "magnetic bottle" concept, so to speak — has been tested to a degree to cast considerable doubt on its efficiency?

If anything has been demonstrated, it would seem that in the so-called low density regime, where the magnetic pressure exceeds the actual pressure of an ionized gas, instabilities are virtually unavoidable. Long ago, it was recognized that anomalous behavior occurred in the presence of magnetic fields and that diffusion, for example, turned out to be more favorable than expected.

At the inception of fusion research more than two decades ago, I did advocate electrical discharges in plasmas of high density exemplified by the "exploding wire" technique. The hope was that inertial containment might permit the discharge of great quantities of electrical energy in relatively small enough masses of fusionable matter. This today is basically the central idea of laser fusion technology. The pioneering effort referred to was frustrated by the comparatively prolonged duration of the energy buildup in the channels where the heating occurred, limited by the electronic circuitry; the material subject to the discharge was an integral part of this very circuitry. While evidence for neutron production obtained, the likelihood of sustained fusion beyond the breakeven point appeared in doubt.

Thus, when lasers entered the scene I was among the first to recognize the prospects of renewed attempts to secure inertial containment where now time intervals for dumping adequate amounts of energy in very confined volumes of fusionable matter by optical focussing could be considerably shorter than in the exploding wire system. Indeed, extremely short pulses of coherent light in the range from billionths to trillionths of a second can be produced today for this purpose.

Despite the considerably brightened outlook that developed with the advent of the laser, a point was reached where it was believed that the technology was insufficient to inject energies even in milligram pellets of heavy hydrogen-bearing substances to reach the self sustaining break-even threshold for the release of thermonuclear power. The Thermonuclear Division of the AEC presented a gloomy report to the JCAE that later was officially reported in several volumes published in the latter part of 1971 — to the effect that a breakthrough in laser fusion was a long way off since megajoule devices would be required. At the time, pulsed lasers were barely at the kilojoule level, so that an increase of some three orders of magnitude had to countenanced, amounting to a Herculean leap forward!

At this dispirited juncture, I came to the realization that the prevalent dour attitude might well be unfounded and that present-day laser technology was adequate if the "NT" criterion were invalid under the intense pressure produced by the lasers. Elementary calculations indicated that enormous pressures could be generated by laser beam exposure and that therefore ionization could possibly be suppressed so that collisions between neutral atoms would result in fusion much more readily in the absence of Coulomb repulsion.

The latter circumstance is not unlike the penetration of neutrons into the atomic nucleus. Before the discovery of the neutron, Lord Rutherford had maintained that practical transmutation was not at all feasible, despite his own beautiful experiments of nuclear alchemy; the cross-sections were too low for reasonable yields to be obtainable. Neutron bombardment altered the course of events and within a few years the chain reaction came into focus with consequences affecting human destiny. The possibility of realizing thermonuclear fusion under conditions where neutral atoms can interpenetrate without repulsion otherwise present when ionized particles are made to interact, raises exciting prospects. It is of course well-known that the super bomb involves the triggering of thermonuclear fusion by the extremely high temperatures of the fission bomb itself.

Thus, controlled fusion may be achieved by a somewhat different mechanism than that responsible for the H-bomb. The underlying philosophy of future fusion research as supportive of Project Jericho entertains a completely divergent approach of searching for materials and incisive ways of employing modest laser-powered devices to produce a more or less steady output of energy. Unlike the pellet configuration in practice currently, an improved technique can permit a series of mild explosions remindful of the internal combustion engine principle but of an intrinsincally different energy source.

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There exists much proprietary information that I have generated along these lines, some of which has been filed as patent disclosures and others disclosed in confidence to the AEC. Project Jericho continues to languish owing to obstructions that are largely political in nature. Perhaps a review of past events over the last several years is in order and can be instructive to those unfamiliar with Government bureacratic practices.

When it became clear that a significant technical development, reflecting on the possible achievement of fusion along lines first advocated many years ago as liaison scientist with the U.S. Air Force was in the making, an effort was made to revive the matter. Thus in early 1972, I contacted Dr. William Lehmann, at the Pentagon and did provide him with a written description of the possiblity of high pressure trapping of laser fusion via the role of neutral atomic collisions. Just prior to this, I had alerted some of my former colleagues that a new complexion pertaining to the successful application of lasers for inducing practical fusion had been conceived. Through such correspondence I was urged to contact the chairman of the then pending Montreal Conference on Quantum Electronics who cordially invited me to attend since a notable portion of the program was to be devoted to lasers and fusion.

Several months before my departure to Montreal I was busily engaged in actions designed to explore possible support of exciting ideas that transcended the glum attitude about the prospects of the official fusion efforts. After attempts to communicate effectively with the AEC proved fruitless, my good friend Congressman John Dow of New York intervened and gained an appointment with Dr. Roy Gould. The ensuing conference with members of the Thermonuclear Division was frustrated by the climate of super-secrecy developing with regard to laser fusion. Little was learned of the AEC ongoings, but I did convey my strong conviction that the need for high powered lasers did not preclude the possibility of a breakthrough in penetrating the threshold to the long sought-for breakeven point.

To be sure my position was not misjudged, I reaffirmed the views expressed by conferring with Seymour Shwiller and Richard Bauser of the Joint Committee of the AEC; they did acquire a copy of a statement I had prepared for the occasion. Other members of the JCAE by direct contact and via their statement were exposed to the pungent views I held regarding the likelihood of a brighter chapter in laser fusion just down the road.

So by the time I was on my way to the Quantum Electronic Conference, considerable groundwork had been laid to forge ahead with an undertaking that later crystallized as Project Jericho. I had been impressed by the officialdom of AEC that an intense atmosphere of classifying high energy aspects of laser fusion was descending and that caution should be exercised in the dissemination of any information pertaining thereto.

With such an admonition uppermost, I was profoundly shocked to witness the revelation made by Livermore people under Dr. Edward Teller's leadership at the Montreal meetings re-echoing the essential thoughts I had only recently proclaimed to the AEC! Before the plenary session of attendees, Teller declared a reversal of the somber mood about the prospects of laser fusion, announcing the discovery via theoretical studies that extreme pressures produced in subjecting pellets of deuterium, tritium, or certain other appropriate materials, pronounced thermonuclear conversion should be expected. However, no identification was given for the rate of charge neutralization and the relaxing of the Coulomb barrier inherent in the conventional criterion embodied in the "NT" concept based upon the well known Gamow-Teller formalism.

A press release conference was held with a statement asserting that the declassification of the astounding observations was the most significant since the Geneva Conference, more than a decade ago. I offered a statement to Jack Armstrong handling media matters for the meeting who, although aware of the contents, refused to provide official sanction. David Gregg, a Livermore member, did offer to exchange ideas and extended an invitation to visit the California-based laboratory.

With mixed feelings I returned to Washington, D.C., expecting the tremendous news to be well covered here in the U.S. To my amazement, members of Congress, including Congressman Dow, acknowledged a complete blackout of the Montreal pronouncements. Attempts to obtain cooperation from the media proved abortive — even to the extent where the *Washington Post* quashed a release that was about to be published. Congressman Marvin Esch of Michigan was presented with a tape copy of a radio program I had recorded at a radio station which strangely never aired it.

Despite such frustrations and rejection, the search proceeded for responsible support to fathom the perplexing circumstances surrounding the Teller disclosure at Montreal and the failure of the media to proclaim to the American people the significance of the "most important de-classification in the atomic energy program" in recent days.

Following a rumor that JCAE had been greatly disturbed by the Montreal events and the aftermath, I was led to Senator Peter Dominick's aide, Robert Old, who shed some light on what may have happened and, furthermore, arranged for me to confer with Congressman Chet Holifield. A meeting took place shortly before the 1972 elections.

Just several months before this occasion, Congressman John Dow had been very active in promoting attempts to enlist support from NASA, the Air Force, and the Army, culminating in an appeal to General George Lincoln, Director of the Office of Emergency Preparedness. Charles Primoff, Lincoln's aide, called together principals from various governmental agencies to hear my pleadings for a rational energy program, particularly with emphasis on laser-fusion. Despite a later released memorandum prepared by OEP, no visible reaction occurred. This should not have been too surprising since evidence was already apparent that certain forces had raised opposition to the OEP-sponsored conference and that in fact, agencies having a prime responsibility in the energy field had abstained from accepting invitations to appear.

Thus, when the meeting with Holifield transpired, a ray of hope shone through the impenetrable darkness of the amazing series of events. He expressed his displeasure with Teller's defiance of the AEC policy to maintain strict secrecy about laser fusion. Both Schwiller and Bauser were summoned to join our discussions and they were instructed to provide support of my plea to support a fresh effort in fusion based upon ideas I had not fully disclosed as yet.

The groundwork was laid for me to review the matter wih the AEC General Counsel, Martin Hoffman. This was done in the presence of others who attended the confidential session. It was there that Project Jericho received official recognition as an undertaking between the AEC and the Biopolis Corporation of America.

In the course of making official disclosures to Roland Anderson with my counsel-friend present, a proposal was submitted for obtaining seed money for launching Project Jericho. The matter was referred to the scientific staff of the AEC and no formal response ever resulted. Indeed, during this period I was subjected to an unannounced confrontation with certain parties, members of the AEC, who used the occasion to extract further information from me concerning some of the novel ideas disclosed to Anderson. This turned out to be the last contact I experienced with the AEC in March of 1973 and no communication has been forthcoming since. The silent curtain descended, leaving many questions unanswered.

Despite my appeals to Holifield and later Congressman Melvin Price for clarification, the silence has remained unbroken. I had prepared a presentation to be made before the JCAE as requested sometime earlier by Holifield and the opportunity to deliver it just never developed. The communication wall persists today.

Project Jericho remains a dream for the mobilization of an invigorated promotion of laser fusion which seems to be lagging for apparently inexplicable reasons. It would almost seem that a deliberate effort is being made to slow down progress while the fission power program is given ample time to suit the commercial interests of the electrical utility companies. Scientists imbued with the "Zero Growth" philosophy have added to the discouraging picture by portraying an outlook of limited opportunity for future trainees. It is common knowledge that academic institutions have curtailed their science programs to restrict the number of neophyte graduates.

Yet, in reality, the need for young enthusiasts in science, particularly in physics, is so great and so urgent. The nation could turn the corner into an exciting era of energy plenty if an all-out assault of the character of Project Jericho were to burst forth on the present lethargic scene. There could be a resurgence of the spirit that produced momentous advances in technology where the challenge was accepted as unlimited opportunities loomed on the resplendent horizon, glowing with hope and meaning for all mankind.

The people of America must be informed adequately as to the past history and status of the nation's endeavor in thermonuclear fusion if they are to act intelligently and urge an all out effort at once. Further delays are intolerable when the stakes are so high. Stabilizing our economy and combatting inflation demand an end to shortage — especially in the domain of energy.

Full speed ahead to laser fusion power !