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CONTRIBUTIONS OF THE ACCELERATOR FRATERNITY TO THE SOLUTION OF ENERGY PROBLEMS*

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Summary

A brief summary is presented of the present situation in the field of energy production and consumption. Particular attention is given to areas where accelerator builders are particularly active. This will include fusion, solar energy, and energy storage and transmission. A few leaders in these fields who have been active in building or using particle accelerators will be identified. In conclusion a few problems will be mentioned which could be assisted toward solution by the talents of the accelerator fraternity.

Introduction

Since 1928 or so, accelerator builders have been faced with innumerable, unsolved technological problems. As these problems have been solved, one after another, the accelerator fraternity has developed a cohesive self-confidence. It is embodied in the belief that, if a technical problem has a solution, we can find it and, indeed, some very improbable devices have been made to work and to accelerate charged particles to high energies.

We have known for some time that an energy shortage is impending. Many of us during the past decade have made studies of the problem. Some have left the accelerator field to work full time on energy technology; others have engaged in part-time studies; still others are in the process of transition. By far the greatest number have concluded that nuclear fusion is the most exciting and promising of the possible energy sources to replace the fossil fuels. A small number are excited by the possibilities of solar energy. Others are intrigued by the overall problem, by the scheduling in and out of the various possible energy sources, and by the necessity for informing the public that there is a problem and what are its possible solutions.

This morning I propose to begin by discussing the energy problem and present situation. Then I will present the thesis that the main contribution of the accelerator fraternity is people; this I will support by identification of a number of accelerator builders and a few users who are now deeply involved in energy studies. Parenthetically, my identification of people will be in no way complete. You will certainly know of many accelerator builders who have made contributions to the energy problem whom I shall not have time to mention. My examples are examples only and by no means complete enumerations. Finally, I shall mention a few areas where contributions are needed and where accelerator builders are peculiarly suited to making them.

The Present Situation

Energy consumption in the United States amounts to somewhat more than the equivalent of 10^{13} kilowatt-hours per year. Of this about 46% comes from burning petroleum and petroleum products, 32% from natural gas and 17% from coal. That adds up to 95%; the rest comes from hydroelectric and nuclear power. The problem is that there is not much more oil. By the year 2000 shortages will be developing; and there is still less natural gas. There is lots of coal — enough for another 400 years or so.

There is a short-term problem and a long-term problem. The short-term problem is as follows. Some 78% of our fuel-burning apparatus is designed to burn liquid or gaseous fuels. Some can be converted to burn coal; others, like automobiles, present problems. Fortunately it is possible, using known and tested procedures, to convert coal to either a liquid or a gaseous fuel. Moreover, a massive amount of money is being spent by the Government on improving these processes. At present, however, fuels produced by coal liquefaction or gasification are more expensive than oil. The consequence is that the coal industry is not going to start new mines and build conversion plants until a real shortage of oil has forced its price much higher than it now is. Then we shall sit around in cold homes and offices for another five years or so while the new coal facilities are activated.

The long-term problem follows from the fact that in a few hundred years all of the fossil fuels will be gone. We are in the middle of an isolated event in human history and, if the human race is not to fall back into the mode of life of 1000 years ago, we must have new sources of energy.

We are fortunate in the fact that we enter this crisis period with the well-developed beginnings of a nuclear power industry. This industry has its weaknesses, however, the worst of which is that the supply of reasonably rich uranium ore is limited and we shall be forced in fifty years or so to use of more expensive uranium extracted from poorer ore. Another problem is the disposal of radioactive waste; this one is not solved, though possible solutions have been proposed. Finally, a segment of the public is concerned about the safety of nuclear power plants.

The uranium shortage will become unimportant when breeder reactors come on the line. But development of the breeder has been marred with enormous cost overruns — I do not quite understand this in the light of the fact that the French have managed to build a breeder that works for a reasonable price.

The bright star on the horizon is the fusion reactor. In its first form it will probably burn a combination of deuterium and tritium. The deuterium is available in virtually unlimited quantities from ordinary water and the tritium is manufactured as the reactor runs, by reactions between reactor neutrons and a blanket of lithium or a lithium alloy that surrounds the reaction region.

Some contributions can be expected from capture of solar energy and from use of geothermal energy. It is hard to see, however, how during the next fifteen years, solar and geothermal energy can contribute more than about 3% of our total energy budget.

It has been evident for many years that the impending energy shortage would catch up with us about now. But it was not until about five years ago that our Government began to try to do anything about it. President Nixon issued several energy messages which produced very little action from the Congress until

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a couple of years ago. Finally, in mid-1973 the President proposed a five-year $10 billion energy research and development program and instructed the Chairman of the Atomic Energy Commission, Dixy Lee Ray, to prepare a report recommending how the money should be spent. Dr. Ray proceeded with energy and dispatch, assembled many groups of experts (one of which included Jim Leiss, Chairman of this Conference), and issued the report on schedule on December 1st of 1973. It was called "The Nation's Energy Future" and has the number WASH-1281. You can obtain a copy for $1.95 from the Government Printing Office.

Also in 1973, the President proposed a consolidation of agencies doing research on energy into what was to be called the "Energy Research and Development Administration" or ERDA, for short. This was to include all of the functions of the Atomic Energy Commission except for the nuclear regulatory operations, the Office of Coal Research from the Department of the Interior, the solar and geothermal programs from the National Science Foundation, the Environmental Protection Agency's program on automobile power systems and sundry other miscellany from other agencies. This was approved in a bill passed by the Congress last fall and, last January 19th, the AEC went out of business and ERDA began operations. ERDA's organization and chief personnel have been carefully chosen to make it clear that ERDA is not just a new name for the AEC and that it covers the whole field of energy. Its Administrator, or head, is Robert Seamans, formerly President of the National Academy of Engineering and, before that, Deputy Administrator of NASA and Secretary of the Air Force. ERDA will include six main Divisions, each with its own Assistant Administrator. These Divisions are as follows: Fossil Energy, Nuclear Energy (includes the breeder, but not fusion), Environment and Safety, National Security and, finally, the two Divisions with which we shall be most concerned, namely, Conservation (which includes power transmission and energy storage) and Solar, Geothermal and Advanced Energy Systems (which includes fusion, high energy physics and all of the other activities formerly covered in the AEC's Division of Physical Research).

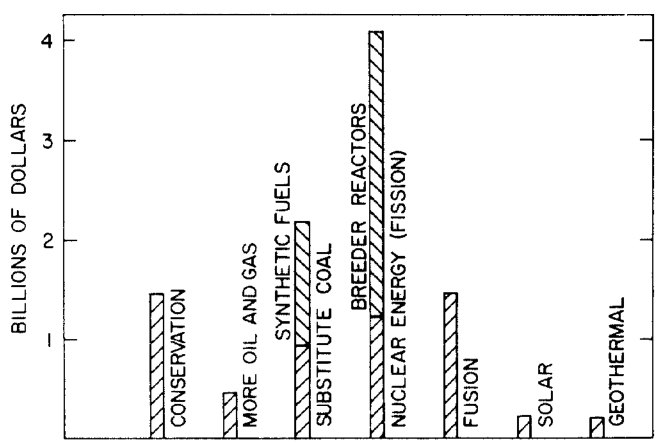

Fig. 1. Five-year energy research and development program as described in "The Nation's Energy Future."

It is interesting to compare ERDA's budget with the recommendations of the Ray report. Figure 1 shows the total five-year expenditure of $10 billion broken down into the five primary tasks that the Ray report chose as most important. We now have figures for FY 1976 for ERDA's projected budget. It will be a total of about $5 billion of which $2 billion will go for weapons to the Nuclear Security Division. Percentages of the remainder of the ERDA budget are quite similar to those in the Ray report. The largest item in both budgets was for nuclear development. The Ray report called for 41% of the expenditure to cover this item, primarily development of the breeder reactor; ERDA's budget devotes about 51% to this objective. The next largest items – coal and fusion – are identical in both budgets at 22% and 15% respectively. Conservation, given 14% in the Ray report, has been cut to 5% in the ERDA budget. Solar, geothermal and research and development of new sources of oil and natural gas are trivial – 5% or less in both budgets.

So much for the overview. We now turn to the specific areas where accelerator people are active. First will be fusion.

Fusion

In the United States there are four main approaches to attainment of fusion power. None have worked yet but progress during the last three or four years leads us to be optimistic, first, that a feasibility experiment will succeed in the early 1980's and second, that successful fusion power plants will come into operation in the 1990's so that fusion can begin to supply a significant fraction of our energy budget in the first years of the twenty-first century.

Of the four fusion techniques three depend on containment of a plasma discharge in a magnetic field. Of these, the favorite is a toroidal discharge, heated by the same sort of field as provides acceleration in a betatron. This approach was invented in the USSR; the device has become known as a "Tokamak." It is under study primarily at Princeton, Oak Ridge, General Atomics, and M.I.T., with smaller programs at several other institutions. Recently, Princeton has been chosen as the location for a $215 million feasibility experiment. This is known variously as the TFTR (Tokamak Fusion Test Reactor) or the TCT (Two Component Torus). It is hoped that this machine can be in operation by 1981.

The criteria which must be met by a magnetic containment fusion device are that the ion temperature must be above 6 keV and the product of electron density and containment time must be greater than 10^{14} cm^{-3} sec. The latter condition is known as the Lawson criterion, named after John Lawson of the Rutherford Laboratory, whose name is well known in the accelerator field. Probably most of you have seen his most recent paper written with Pierre Lapostolle and Bob Gluckstern on "Emittance, Entropy and Information."[1] Progress toward meeting these criteria in Tokamaks include achieved temperatures of the order of 1 keV and density-time products of about 10^{12}. It appears, however, that all that is required to reach fusion levels is to make the device big enough. The torus in the TFTR will have a minor radius of 1.2 meters and a major radius of 2.8 meters. A fusion power reactor to supply about 2500 MW (electric) might have a minor radius of 5 m and a major radius of about 10 m. According to a Princeton study, it would cost about a billion dollars.

The other magnetic containment devices are the "theta-pinch", under study at Los Alamos, and the "mirror" machine at Livermore and United Aircraft. The theta-pinch is also a toroidal device but includes a pulsed magnetic field which compresses the plasma to a high density. The mirror is an open-ended device in which the plasma is confined by a sort of quadrupole field generated at least in some cases by a winding like the seam on a baseball.

The fourth fusion approach is compression of small pellets including deuterium and tritium by laser beams or electron beams. The pellets are compressed by a factor of the order of 10^4 and heated to the combustion temperature at which point they explode like tiny hydrogen bombs. This somewhat fantastic project is under study at Livermore, Los Alamos, and at a private corporation in Ann Arbor, Michigan, called KMS Industries.

Fusion was the first field to seduce accelerator people away from the safety of high energy physics. One of the first was Don Kerst. There may be some young people here who do not remember that Don was the inventor of the first betatron that worked; through the war years and thereafter he pushed the accelerator limit to 300 MeV in betatrons culminating in a splendid machine at the University of Illinois. He was deeply involved in the MURA Laboratory in Madison, Wisconsin where, for a time, he was the director. In the mid-fifties he became aware of the possibilities of fusion and left MURA to join the research effort at General Atomics in San Diego. With him went an extraordinarily bright young man — the man who first proposed the colliding beam system at MURA — Tihiro Ohkawa. After some time Kerst returned to the University of Wisconsin where he still is, engaged in a fusion-related research program. Ohkawa, however, is still at General Atomics where he is now in charge of the whole fusion program. I spent a pleasant evening with him a couple of weeks ago — he seems to be enjoying himself.

While we speak of General Atomics, I would like to mention Ed Hubbard. Many of you have known him at Berkeley, others will remember his career at the Fermilab where he played a leading part in construction and bringing into operation of the booster synchrotron. He also is now at General Atomics where he is in charge of Doublet III, GA's most advanced Tokamak. This machine has a noncircular plasma cross section which, it appears, may present many advantages in making more effective use of the toroidal magnetic field.

At this point I mention a couple of the outlying fusion efforts not included in the major four that I began with. For example, Bogdan Maglich, a high energy physicist, has formed a corporation — the Fusion Energy Corporation — around an idea for a colliding beam system. Active experiments are under way in his plant in Princeton. Another peripheral effort dating back to the fifties was the Astron, invented by Nick Christofilos while he was still at Brookhaven helping to design the linac injector for the AGS. You remember, of course, that Nick was the first inventor of alternating-gradient focusing. In those days, fusion research was classified. We were trying to keep Brookhaven an open research center, so Nick moved to Livermore where he built his machine and pushed it halfway to success. After his death a couple of years ago, the Livermore program was shut down, but a parallel program is in progress at Cornell where considerable success has been achieved. I draw your attention to a paper to be presented on Friday morning by Ravi Sudan; he is one of the leaders in the Cornell effort. The basic Astron idea is containment of ions in a dense ring of relativistic electrons. The electrons produce an enclosed magnetic field which keeps the ions from escaping and, at the same time, heat up the ion plasma to the ignition temperature.

The backgrounds of two of the major fusion laboratories are intriguing. Princeton is reputed to have been founded by astrophysicists while Livermore was built up by accelerator builders, initially from Berkeley but later from many other centers. Dick Post, whose writings about fusion you have read in Science[2] worked with Ed McMillan at Berkeley; later he moved to Stanford where he was in charge of construction of the Mark II electron linac, the prototype for the famous Mark III. Ken Fowler, who is in charge of Livermore's fusion program, was a student at the University of Wisconsin where he worked as a graduate student with Keith Symon and the MURA group.

Hot off the press is the news that Princeton is looking for accelerator builders to help with the Tokamak Fusion Test Reactor. They have succeeded in at least one important case. Paul Reardon is about to leave the Fermilab to become project manager in this exciting project. He will find fusion reactor components spread throughout the building where he helped to build and operate the Princeton-Penn Accelerator.

Ion beams have many applications in the fusion program. Final heating of magnetically contained plasmas will probably be done by introduction of neutral atom beams having energies of the order of 100 keV. These are initiated as beams of positive or negative ions which are accelerated and then neutralized. Negative ions are preferable because, at 100 keV, they can be neutralized much more efficiently than positive ion beams. It happened at Brookhaven that Theo Sluyters and Krsto Prelec were working on negative ion injection into the AGS where a 5 or 10 mA beam converted at injection to positive ions, might be able to defeat Liouville's theorem. They heard of the fusion requirements and began pushing for intensity. Last week they passed half an ampere — that work will be reported on Thursday morning.

Ion beams are needed also in intense neutron generators to simulate the environment of a fusion reactor for materials testing. These are being worked on at Livermore, Los Alamos and Brookhaven — at LASL and BNL the designers include a number of people who worked on the linacs at the two laboratories — Bob Emigh, Ken Batchelor, Rena Chasman, Pierre Grand, and many others.

Laser fusion has attracted Bob Hofstadter whose name has long been associated with the form factor studies at the Stanford Mark III linac. Bob is now a consultant to KMS Industries. This single fact seems to me to inspire some confidence in the future of laser fusion.

Solar Energy

Under the heading of solar energy come a variety of projects of which the most immediate is the heating and cooling of buildings. More remote are so-called solar thermal systems for producing high pressure steam and hence electricity in enormous arrays of tracking reflectors. Still more remote are photochemical electrolysis of water and development of cheap and efficient photovoltaic cells. You will find that most defectors from the accelerator business into solar energy exploitation are concerned with heating and cooling of buildings and associated problems like how much sunshine energy per year is deposited at the place where you live.

One of the more impressive programs is at Argonne where it is being organized by John Martin who, you remember, was involved in the construction of the ZGS and is in large part responsible for its present fine performance. Roland Winston at the University of Chicago was designing a reflector system for a Cerenkov counter and realized that his trough-shaped reflector could be used as a solar concentrator which does not have to be moved to track the sun. Arrays of these reflectors are now under construction for test use in heating systems. Another Argonne project is a joint study with a major Chicago contractor of solar heating and cooling for a new community of 2200 housing units. Several other projects also are active including collection of solar data.

At Berkeley a number of heating and cooling projects are supervised by Mike Wahlig, formerly a user of the Bevatron. At Brookhaven, Garry Cottingham and Ken Green, two of the builders of the AGS, have designed a solar steam plant to supply process steam to the output of our oil fired central heating system — this was inspired by the bills which have been coming in recently for the 7 million gallons of oil that we burn annually. All of our oil on Long Island is imported. In addition Cal Lasky, another AGS builder, is taking a hard look at windmills.

Energy Storage

For the electrical utilities, a good method for storing energy to the extent of a few thousand megawatt-hours would be very valuable for what is known as peak-shaving. Energy generated during slack hours could be stored and returned during hours of peak demand. Pumped storage — water is pumped to a reservoir on top of a hill — has been tried but is not practical in many places either because it is environmentally objectionable or because of the absence of hills.

Many of us accelerator builders have experience in applied superconductivity; this will provide the economical accelerator and beam transport magnets of the future. High fields are possible and hence so are high stored energies. It was inevitable that experts in the fields of accelerator design and applied superconductivity would collaborate in seeing how much energy could be stored in a superconducting solenoid or toroid. Leaders in this field have been Fred Mills, Program Chairman for this Conference, and Roger Boom, applied superconductivity specialist at the University of Wisconsin. Roger is designing peak-shaving coils of fantastic dimensions and fields (a probable hazard to navigation for miles around). In the meantime Fred is looking at smaller energy storage coils suitable for supplying energy to the Fermilab accelerator at 500 GeV without unduly loading the power lines of Commonwealth Edison. Fred's coils, if and when they are built, will serve as prototypes for the enormous peak-shavers proposed by Roger Boom.

Power Transmission

In the field of power transmission there is, at Brookhaven, a classic example of transfer of skills from accelerator building and operation to a new field. In 1969 we were already deeply involved in construction and operation of superconducting magnets for use on bubble chambers, in beam transport, and for use in accelerators. Hence we had assembled or trained experts on superconductivity and cryogenics. Also both in the accelerator group and in our reactor department we had a number of experienced power engineers. It seemed natural that a group representing these various disciplines should get together and think about superconducting power transmission. By now we have a full-fledged project supported by the Conservation Division of ERDA and managed by Eric Forsyth, who used to be the chief electrical engineer for the AGS. It turns out that, above 1000 MW or so, superconducting lines will be cheaper than conventional high-pressure oil-filled underground lines. Also the current-to-voltage ratio is a much better match to the line's characteristic impedance. Conventional underground lines need expensive inductive compensation every 20 miles or so; superconducting lines will transmit without compensation for hundreds of miles. We hope in a couple of years to have a thousand feet or so of superconducting three-phase ac line carrying all of Brookhaven's power at 69 kV.

Management of Energy Research and Development

Several old accelerator hands deserve mention for their general support and management of energy programs. Gale Pewitt, who was in charge of the large bubble chamber at the ZGS now directs Argonne's energy programs. Andy Sessler, a man of many distinctions in the accelerator field and now Director of the Lawrence Berkeley Laboratory was the organizer with Jack Hollander of Berkeley's various energy programs. A couple of others whose names might not come immediately to mind in this connection include, first, Bill Wallenmeyer, formerly of MURA and now in charge of high energy physics for ERDA. His programs over the years have supported many disciplines of value to high energy physics but also enormously important to the energy program. Particularly his support of applied superconductivity has brought it to the point where it is applicable to power transmission and generation and to levitated transportation. The second name I bring to your attention in this connection is that of John Martin of Oak Ridge, Oak Ridge's accelerator manager and one of the original organizers of this series of Conferences. I mention him because of his many activities in the IEEE. He has been a past president of the IEEE's Nuclear and Plasma Sciences Society which has been extremely effective in the transfer of information in the field of energy.

I shall mention no more names. I reach this point with the realization that there are many other accelerator people involved in energy programs and hope that those whom I have left out will forgive me and realize that they are in good company.

Conclusion

Last fall I wrote to Don Kerst asking him what brought him away from accelerators into the fusion program. He replied, in part: "There was... a close parallelism with accelerators which I pushed when I got into fusion research, namely the topological similarity between phase space trajectories in accelerators and coordinate space trajectories of lines of force in stellarators with their magnetic field transforms. Although excellent analytical work had been done on this stellarator problem the extensive experience of accelerator designers with nonlinear mechanics and the stability limits and the topological effects of field errors had the accelerator studies far ahead of stellarator studies and it has taken fusion people something like 5-10 years to absorb the results. Another topic has required some time to move over and to be rediscovered by the plasma physicists, namely damping or driving of synchrotron oscillations by radiofrequency oscillators and the nonlinear topology represented by synchrotron phase space. Such Landau damping effects as were featured in the accelerator field are now prominent in the plasma field." The missionary work which Don describes has largely been done although many mysteries remain in the behavior of plasmas. Ever since the turn of the century people have made careers of studying arcs and sparks and the job is still far from complete.

I conclude by mentioning the fact that many less esoteric skills will be required in the production, consumption and conservation of energy. Perhaps foremost among these is mechanical engineering. Electrical engineering capabilities will be required of specialists in computer control, high voltage technique, and electric power generation and transmission. Physicists with knowledge of particle beam transport, applied superconductivity and many other areas also will easily find places in energy research and development. Your interest now will help us to keep warm in the impending decades.

References

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2. R.F. Post and F.L. Ribe, "Fusion Reactors as Future Energy Sources," Science 186, 397 (1974).