Chapter 11
Conclusions

Ah, but a man's reach should exceed his grasp, or what's a heaven for?

Never have these oft-quoted words by Robert Browning been more pertinent. The very existence of man depends on his ability to get energy when nature's bounty runs out. We may not succeed in creating our own Promethean fire, but it's within reach.

Fusion is a solution to both climate change and energy shortage. Fusion energy is inexhaustible and nonpolluting.

Fusion will cure our dependence on oil. There will be no need to wage wars in the Middle East. With unlimited energy, there will be electricity or hydrogen to run cars.

With unlimited energy, desalination can provide fresh water in all coastal regions.

Fusion cannot explode or be proliferated.

Fusion does not need to disturb the environment or wildlife habitats. Reactors can be located on the sites of aging coal or nuclear plants. In particular, they can be located near population centers. No new cross-country transmission lines need to be built urgently.

Fusion is the only energy source that can sustain mankind for future centuries and millennia. The sooner we get it, the less we need to spend on temporary solutions.

Scientific Summary

In Chap. 1, we summarized the scientific evidence for global warming caused by carbon dioxide emitted by human activity, especially the burning of fossil fuels. In Chap. 2, we summarized the known facts on fossil-fuel reserves, especially the critical shortage of oil. We showed the difficulty of and dangers in extracting the last reserves as well as the expense in sequestering the greenhouse gases emitted in their use. In Chap. 3, we surveyed alternative energy sources and found that none of them, except nuclear energy, can provide dependable backbone power, although many are suitable as supplementary power sources.

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In Chaps. 3–5, we introduced the concept of fusion power and explained why a magnetic bottle holding a hot plasma is needed to fuse hydrogen into helium to get energy from water. In Chaps. 7 and 8, we explained the physics of plasma containment in a device called a tokamak and summarized all the difficult problems that have already been solved. In Chap. 9, we gave details on all the extremely difficult engineering problems that have yet to be solved. Finally, in Chap. 10, we showed other ways to achieve fusion power which have not yet been explored extensively but which may make better reactors than the tokamak.

Cost of Developing Fusion

Financial Data

The benefits of fusion will not come cheaply, but the cost is smaller than that of other projects that the USA has undertaken with success. Figure 11.1 compares the costs of the Manhattan Project, the Apollo Program, and the Iraq and Afghanistan wars (up to 2010) with the projected cost of developing a fusion reactor. In constant 2010 US dollars, the Manhattan Project cost $22.6B, and the longer Apollo program cost $100.8B.[1] Other estimates are twice as high.[2] The two current wars have

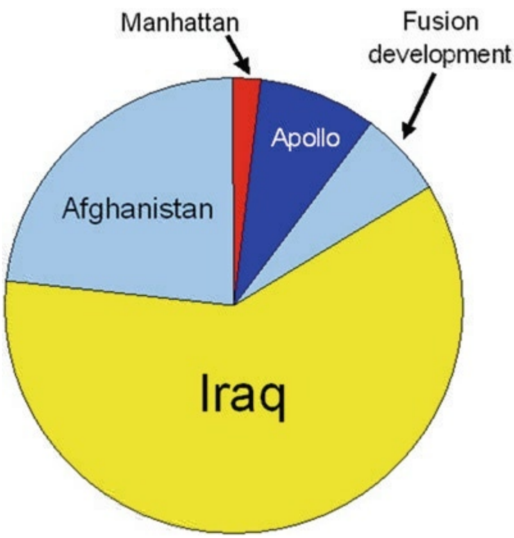

Fig. 11.1 Comparative costs of the Manhattan Project, the Apollo Program, the Afghanistan and Iraq wars, and the conjectural cost of development of fusion reactors. All costs are normalized to 2010 US dollars

cost \$732B and \$282B, respectively, so far.[3] The cost of developing fusion is a highly conjectural estimate. The cost of ITER, originally set at €5B (\$6.3B), has risen to €16B (\$21B).[4] Engineering research will require fusion development facilities (FDFs). These have not been costed out, but one design is 45% the linear size of ITER, and the cost rises as the size squared. With the higher projected cost of ITER, this would make an FDF cost about \$4.2B. Perhaps three of them would be required for a total of \$12.6B. The DEMO would cost at least twice as much as ITER or \$42B. The total is \$75B, less than that of the Apollo program, which did not solve any pressing problems. After DEMO has been run successfully, further development would be turned over to private industry, and federal support would no longer be needed. The fusion cost given here is a guess, but it is clear that the USA has the resources to develop fusion without outside help. It is only a matter of priorities. Jack Kennedy showed that it can be done.

Figure 11.2 gives a breakdown of the \$5.1B FY 2011 budget request of the Department of Energy's Office of Science.[5] Fusion Energy Sciences is the item that supports magnetic fusion research. It is the smallest item there. Basic Energy Sciences is deservedly the largest item because it supports current renewable energies like wind and solar. High-energy physics traditionally has a large budget because it is the community that gave us the hydrogen bomb to win WWII. It still has a large budget for accelerators and experiments that can improve our knowledge of the structure of matter. This is the forefront of science, but mankind may or may not need to know this to survive.

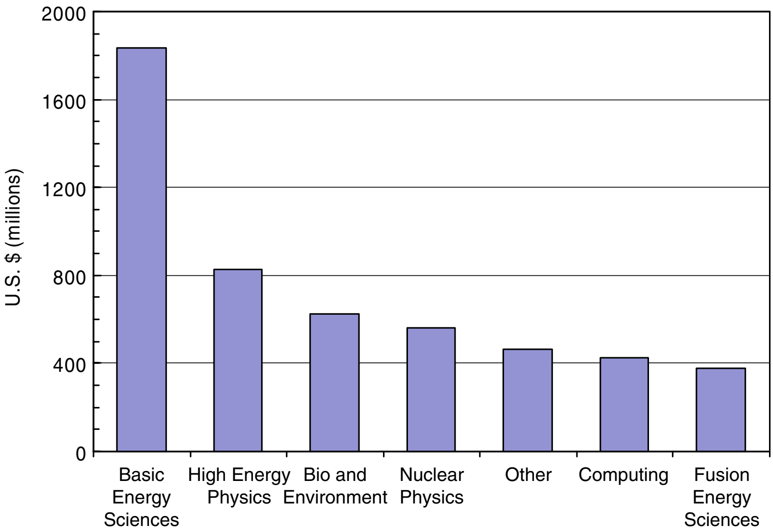

Fig. 11.2 Support for different divisions in the US Office of Science

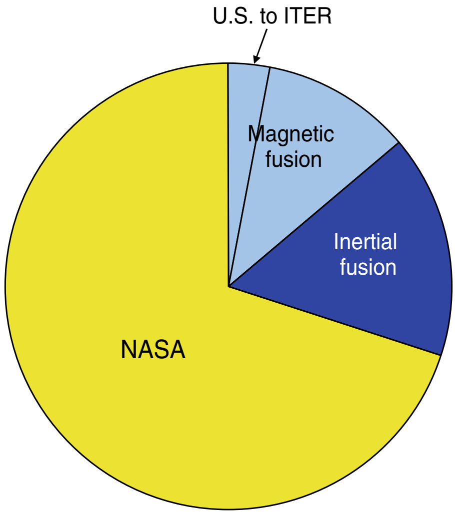

Fig. 11.3 Comparison of the annual budgets of the space and fusion programs in the US

Figure 11.3 compares the annual budgets in the USA for magnetic and inertial confinement fusion research with the $1.9B for the NASA space program. The magnetic fusion budget includes a paltry $80M contribution to ITER, equivalent to *four hours* of expenditures in the Iraq war. Exploration of the solar system (NASA) and study of the behavior of matter under extreme conditions (ICF) are exciting extensions of modern knowledge which scientists are happy to have funded because of their importance to national security. These programs, however, contribute little to the solution of environmental and energy issues. We are spending more money looking for the Higgs boson than for a solution to global warming and oil shortage. Re-examination of priorities is in order.

Figure 11.4 shows the cost of the ITER experiment, including construction but not operation. The expense is shared by seven nations. It is the first giant step toward fusion power. Compared with this is the amount spent by the USA alone to wage the war in Iraq for *one month*.[6] The graph speaks for itself. The USA could easily have taken this step alone had it not been so dependent on Mid-Eastern oil.

Conclusion

- Developing fusion power will cost less than putting a man on the moon. The Manhattan and Apollo programs have shown that the scientific and engineering communities have the ingenuity to achieve almost unimaginable goals once it is driven by national priorities, a sense of urgency, personal challenge, and a sense of national pride. With seven nations having banded together to push forward on fusion, the USA has lost its chance to do this alone. However, we are still far

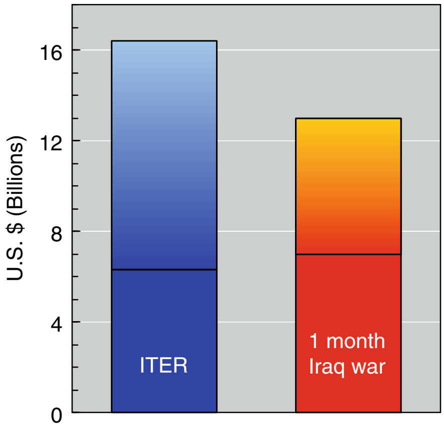

Fig. 11.4 Comparison of the cost of ITER with that spent on the war in Iraq in one month. For ITER, the *lower* part is the original budget, and the *upper* part the added cost in the revised estimate. For Iraq, the line divides the minimum and maximum estimates of the cost.[6] The maximum includes the costs of occupation and repatriation of troops

from the goal because the most difficult problems of materials engineering have yet to be solved. The USA can regain its former leadership in fusion research by building one or more large FDFs to solve these problems simultaneously with ITER to shorten the time to a working reactor.

- The development of wind and solar power in private industry has stimulated the economy. Fusion machines are big and must be funded by the government, but the economic stimulus can also be generated by the subcontracts awarded to small companies. For instance, such components as superconducting strands, silicon carbide tiles, blanket modules, RF antennas, and even 3D computations can all be parceled out to start-up companies. New jobs will be created, and new financing will be secured.
- *A high-priority Apollo-like program to put fusion on a fast track will cost less than Apollo did and will solve the* CO_2 *problem, the fossil-fuel shortage problem, and the oil dependence problem all at once.*

Epilogue

Research on space science, astronomy, and high-energy particles has produced incredibly detailed knowledge of our environment on both macroscopic and microscopic scales. It has been a long journey for *Homo Sapiens* to have evolved from simple food gathering to these intellectual heights. This knowledge, however, will be of little comfort if we cannot find the means to assure the preservation of our species.

We have benefited from the discoveries made by adventurers driven by the urge to explore the unknown and to reach the inaccessible, even at great risk or expense. Magellan, Columbus, Roald Amundsen, Edmund Hillary, Roger Bannister, Neil Armstrong … One climbs Mt. Everest because it is there. To shrink from pursuing the goal of unlimited energy borders on cowardice.

We close on a philosophical note. We have been incredibly lucky. Our planet settled at just the right distance from the sun so that H_2O, a very stable molecule, is in liquid form most of the time, forming the basis for life. As plant life lived and died, its fossils lay buried for millennia as human life developed. This legacy of fossil energy allowed humans to form a civilization and develop brains that could think abstractly and explore our surroundings and the whole universe. Our intellectual capacity grew to such an extent that we could design and make computers that someday can do the thinking for us. The energy source that allowed all this to happen will soon be depleted; but, luckily, we now have the smarts to create our own energy source. But do we have the wisdom to actually do it?

Notes

1. D.D. Stine, *The Manhattan project, the Apollo program, and federal energy technology R&D programs: a comparative analysis*, Congressional Research Service RL34645 (2009).
2. Physics World, July 2007.
3. http://www.costofwar.com.
4. IEEE Spectrum, September 2010. Some say that it might be as high as $20–25B, but this still puts the cost of fusion below that of the Apollo program.
5. Request to Congress as of February 1, 2010.
6. Congressional Budget Office per http://www.usgovinfo.com/library/weekly/aairaqwarcost.htm.