

# TWELVE AXIOMS OF FUSION ENERGY R&D

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## ABSTRACT

The nature of fusion energy research & development is characterized by a dozen axioms and their corollaries covering predicted vs actual performance of experimental devices, consumption of electric power and tritium, and the promotion of the R&D enterprise to the public. Explanations of these axioms show that the course of fusion R&D is as strongly influenced by behavioral science as by scientific and technological developments.

## A. INTRODUCTION

By definition, an axiom is a self-evident truth that usually cannot be proved. The axioms presented herein will not be self-evident to many persons who have imbibed erroneous propaganda on fusion energy for decades. Nevertheless, these axioms have been demonstrated throughout seven decades of fusion energy R&D (Research & Development). An axiom cannot be violated, and plausible arguments can be made for its validity. Such arguments are given in the major section entitled "Justification of Each Axiom."

Journalists and editors have given fusion energy proponents a "free ride" for two-thirds of a century, treating as gospel the self-serving misinformation and exaggerated claims emanating from government-supported fusion labs as well as private companies. Journalists and editors have been ignorant but enthusiastic enablers of campaigns to hoodwink government agencies, private investors, and the public at large. Ironically, journalists were much more skeptical of the 1951 claims of Ronald Richter [1], the original fusion fraudster, than they are of contemporary claims that are equally outlandish.

By applying the axioms presented herein to the latest press releases and online stories, disinterested observers can make more rational valuations of the assertions of fusion proponents.

While these axioms ostensibly concern only fusion technology, at least several of the axioms apply to other fields of technology, notably military and space R&D. Examples are Axioms 4, 5, 7, 10 and 11, when appropriately reworded to the non-fusion field.

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## GLOSSARY

**Confinement parameter**  $n\tau_E T_i$  is the product of plasma electron density  $n$ , energy confinement time  $\tau_E$ , and ion temperature  $T_i$ . Sometimes called the "confinement triple product."

**DEMO:** Demonstration Power Reactor.

**Fusioneer:** A person actively engaged in some fusion energy R&D enterprise.

**ICF:** Inertial Confinement Fusion. Sometimes denoted IFE, for Inertial Fusion Energy.

**ITER:** International Thermonuclear Experimental Reactor, under construction in France.

**MCF:** Magnetic Confinement Fusion. Sometimes denoted MFE, for Magnetic Fusion Energy.

**MTF:** Magnetized Target Fusion. Sometimes denoted MIF, for Magneto-Inertial Fusion.

**MWe:** Megawatts of electric power.

**NIF:** National Ignition Facility, located at Livermore, CA.

**Q** denotes fusion energy gain:

In quasi-stationary MCF fusion concepts,  $Q$  is the ratio of fusion power to the power injected into the plasma from external sources such as neutral particle beams or radio-frequency waves.

In ICF and other pulsed systems,  $Q$  is the ratio of fusion energy per pulse to the energy deposited onto the fuel capsule by laser or particle beams or imploding liner.

**TBR** denotes Tritium Breeding Ratio: the number of tritons bred from lithium in the blanket per D-T fusion neutron produced in the reacting plasma.

## B. STATEMENT OF AXIOMS

### #1- **The Inverse Timescale Axiom**

For any fusion concept, the fewer the experimental results, the shorter the predicted time to a working power reactor.

Neutron Reformulation. For any fusion concept, the smaller the achieved fusion neutron production, the shorter the predicted time to a working power reactor.

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### #2- **Axiom of Manifest Fraud**

A purported fusion concept that cannot produce measurable D-D fusion neutrons is delusional or fraudulent.

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### #3- **The Supremacy Axiom**

No other magnetic confinement system can attain the fusion parameters demonstrated in tokamaks.

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### #4- **The Axiom of Escalating Cost**

In any line of fusion R&D, the actual cost to completion of the next fusion device is three to five times the original projected cost.

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### #5- **The Computer Delusion Axiom**

Computer simulations of plasma behavior in any fusion device accurately explain all past results and erroneously predict most future results.

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### #6- **Axiom of Invariable Committee Approval**

All review committees approve any proposal for any fusion energy concept.

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**#7- Axiom of the Infallible Concept**

Despite dreadful experimental results, no proponent of any fusion concept will ever concede that it cannot be developed into a practical power reactor.

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**#8- Axiom of Massive Electric Power Drain**

Any fusion device and its auxiliary systems consume colossal amounts of electrical energy.

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**#9- The Tritium Deficit Axiom**

*In situ* replenishment of all tritium burned and lost in any fusion device is impossible and will never be attempted.

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**#10- Axiom of Untethered Promotion**

The declaration of “breakthroughs” in fusion R&D is a continuous stream of laboratory and journalistic propaganda independent of any actual progress.

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**#11- The Fanciful Roadmap Axiom**

All “roadmaps” and “strategic plans” for fusion R&D are meaningless as soon as issued.

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**#12- Axiom of Diversionary Claims**

Assertions of “doing good science” or producing valuable spinoffs are a sure sign that the fusion concept cannot advance.

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## C. JUSTIFICATION OF EACH AXIOM

The following discussion offers plausible arguments for the validity of these twelve axioms of fusion energy R&D.

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### #1- The Inverse Timescale Axiom

*For any fusion concept, the fewer the experimental results, the shorter the predicted time to a working power reactor.*

This axiom is consistent with the optimistic predictions that accompanied the very first wave of fusion schemes of the 1950's & 1960's. Only a few concepts survived, such as the tokamak, and these survivors now have projected timespans of many decades for their development into a working power reactor.

Proponents of the most recent concepts introduced during the last 5 to 20 years years initially predicted a 5-year timescale to a commercial power reactor. That timescale soon lengthened to 10 years, and then dropped entirely in some cases. These predictions are reminiscent of the "vaporware" that plagued the software market of the 1990's.

A typical scenario is that of General Fusion, which in 2000 predicted that its first power reactor was five years away; in 2010 the timescale was lengthened to 8 years, and now the organization cites 2025 to 2030 for the commercialization date.

These sad histories lead to the **Timespan Corollary**: *For any fusion concept, the predicted further development time for a working power reactor increases without limit as time goes on.*

There are several obvious reasons for this phenomenon:

- 1) Proponents assume that simplified theoretical behavior of a fusion concept will not be thwarted by reality. What actually happens is the equivalent of the martial saying that "All battle plans are wrecked upon first encounter with the enemy."
- 2) Proponents are ignorant of most practical reactor issues such as vacuum integrity, radiation shielding, energy conversion, etc.

3) Proponents need to attract funding by promising a palatable timescale to wealthy and credulous investors.

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As experimental data eventually dribbles in, the difficulty of reaching performance goals becomes more apparent, and the timespan continues to lengthen. The consequence is that a fusion power reactor will never be implemented.

Neutron Reformulation. *For any fusion concept, the smaller the achieved fusion neutron production, the shorter the predicted time to a working power reactor.*

By the end of 2019, none of the well-funded projects at General Fusion, Helion or Lockheed had produced a single fusion neutron, while Tri-Alpha had produced only token amounts [2]. However, all had predicted in 2012-2014 that they would implement commercial fusion power by dates ranging from 2018 to 2024. LPP [3] and MIFTI [4] appear to be unique among the privately funded so-called fusion energy companies in actually producing a significant number of fusion neutrons, but LPP's predictions for commercialization have suffered the same trajectory as its rivals. LPP has pursued the dense plasma focus (DPF) which was a leading neutron producer back in the 1960's and 1970's, but no DPF project has been able to increase neutrons per pulse beyond  $1E12$  (D-D), a level achieved more than 40 years ago [5].

By far the most successful non-government producer of fusion neutrons has been Phoenix (Nuclear Labs), which recently announced peak D-T neutron production of  $4xE13$  n/s (~100 watts) sustained for more than 100 hours [6]. The Phoenix neutron generator is effectively steady state, so that it can well become the most practically useful fusion neutron source in the world. Phoenix intends that its generators be used for pragmatic neutron applications such as isotope production and radiography, and makes no pretense of developing a fusion power reactor.

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## **#2- Axiom of Manifest Fraud**

*A purported fusion concept that cannot produce measurable D-D fusion neutrons is delusional or fraudulent.*

When put to the test, the vast majority of fusion concepts can produce no neutrons, and *No Neutrons Means No Fusion.*

Energy gain  $Q$  for D-T plasmas is defined as the ratio of fusion energy (neutron production  $\times$  17.6 MeV) to energy injected into a D-T plasma or directed onto a DT-fuel capsule. Only a few fusion reactor concepts have reached even the  $Q = 0.001$  that's achieved by striking a solid tritiated target with a deuteron beam, or the D-D equivalent of  $1E-5$  using a deuterated target. These concepts are the tokamak, laser-compressed fuel capsule, and the DPF, with runner-ups MagLIF and the stellarator far behind. Energy gain  $Q$  can be raised from 0.001 to at least 0.003 when the solid tritiated target is replaced by tritium gas, as in the Phoenix neutron generators [5]. The  $Q$  for the steady-state Phoenix generator has been exceeded only by TFTR, JET and NIF in pulsed operation.

As for evaluating progress, valid neutrons can be either thermonuclear in origin or from collisions involving non-thermal energetic ions, but they must originate from a target gas or heated plasma, as distinct from neutrons produced by wayward deuterons striking the wall of the reaction vessel. The continual promotion of concepts that are unable to demonstrate production of fusion neutrons is purposeful deception, a condition that permeates many of the subjects covered herein.

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### #3- The Supremacy Axiom

*No other magnetic confinement system can attain the fusion parameters demonstrated in tokamaks.*

In any line of technology there is generally a unique or optimal pathway to success. In fusion R&D the tokamak intrinsically holds the “secret sauce” that enables it to reach meaningful fusion performance, generally measured by fusion energy gain  $Q$  and the “confinement triple product”  $n\bar{U}_E T_i$ , defined in the Glossary.

The Soviet T-3 tokamak was the “black swan” of the entire world’s fusion programs when the T-3 results were announced in 1968 and independently verified in 1969 [7]. Nothing else had worked. Even today only the stellarator and laser-heated fuel capsule and Sandia’s MagLIF have attained the performance of the T-3 tokamak of 1969-70— fifty years ago! (viz.  $n\bar{U}_E T_i = 2 \times E17$  keV-s/m<sup>3</sup>.) The best triple product achieved by stellarators, the fusion concept most closely related to the tokamak, is still a factor of at least twenty below the best achieved by tokamaks ( $1.2 \times E21$  keV-s/m<sup>3</sup>) to date [8], and

at much lower  $T_i$ . The tokamak has plenty of well-documented drawbacks and may never have a practical application, but it's the only thing in MCF that works well. (In the ICF world, Livermore's NIF has achieved comparable triple products.)

**Leapfrog Corollary.** *Predictions that a particular fusion concept will soon "leapfrog" tokamak performance are pure fantasy.*

Such predictions rely on lack of experimental data buttressed by complete ignorance of practical hurdles. These predictions are based solely on the fervor of proponents and the gullibility of journalists.

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#### #4- Axiom of Escalating Cost

*In any line of fusion R&D, the actual cost to completion of the next fusion device is three to five times the original projected cost.*

The reasons for drastic underestimation of costs are that 1) proponents make fraudulently low cost estimates to accommodate likely funding available from potential sponsors; 2) proponents engage in wishful thinking concerning fabrication time and costs, resulting in meaningless schedules for some components, with no cushion for design changes or manufacturing problems; 3) contractors underbid in order to increase their chances; 4) shortcomings in design render some components unbuildable, thus requiring significant design changes and re-fabrication; 5) inadequate oversight of contractors by project management, sometimes unaware of new technical problems, or surprised by poorly matched components from multiple vendors, requiring re-building of the interfaces.

The most widely publicized example of escalating costs is the ITER project, whose estimated cost of construction ballooned from \$5 B to \$20 B and more. Other recent examples are the NCSX and NSTX-Upgrade projects at PPPL. Construction of the NCSX stellarator was cancelled after a 3-fold increase in cost. The NSTX-Upgrade tokamak required an additional \$200 M for rebuilding after \$95 M was spent on an upgrade with defective coil windings.

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## #5- The Computer Delusion Axiom

*Computer simulations of plasma behavior in any fusion device accurately explain all past results and erroneously predict most future results.*

Calculations for the first thermonuclear explosives were carried out with desktop electromechanical calculators, or large calculators programmed with punched cards.

Similarly, with essentially no electronic computation the tokamak was conceived in the USSR in the 1950's and developed in the 1960's into the most promising approach to a controlled fusion reactor.

Today computers are essential for processing and analyzing data from fusion experiments, but they can hardly be used to replace experiments. Nevertheless, modeling enthusiasts insist on equating computer simulation to reality. Virtually any plasma concept can be made to look like a viable basis for a fusion reactor by manipulating a computer model. In recent decades it has become acceptable for elaborate computer simulation to "validate" the effectiveness of new plasma confinement concepts or proposed configurational changes in present experiments. But the parameter massaging of computer simulations (or "tweaking") is conducive to self-delusion, sometimes bordering on fraud.

Beginning in the early 1970's, computer simulations of laser-heated fuel capsules always predicted that ignition and energy breakeven ( $Q = 1$ ) would be attained with the maximum laser energy to be available in the project then under construction, starting with 1 kJ for ARGUS, then 10 kJ for SHIVA in the 1970's, and 50 kJ for NOVA in the 1980's [9].

Even when the results of the Centurion Halite tests (with nuclear explosives) in the mid-1980's showed [10] that the laser energy incident on the hohlraum would have to be 60 to 80 MJ to provide the 20 MJ of soft X-rays needed for pellet ignition, computer simulations (LASNEX, HYDRA, etc.) were manipulated to show that only 1.8 MJ was needed— because that was the maximum laser energy that the proposed NIF could muster!

Today, constant self-proclaimed "breakthroughs" in computer simulation are substituted for progress in the real world. The latest computer-related folly is that something called "artificial intelligence" will cure all defects of a hopeless fusion concept. It has become

an effective tool to distract investors and funding agencies from obvious failure.

The meaningful tokamak breakthroughs from 1975 to 1995 included neutral-beam injection, plasma shaping, graphite limiters and lithium deposition on plasma-facing surfaces— none of which was conceived by computer simulation. No computer modeling could take credit for the *discovery* of the tokamak H mode, or the hot-ion mode, etc. It is of scant significance that after-the-fact computer simulations have been massaged to reproduce most of the results of the 1990's tokamaks.

Similarly, the relatively recent innovations of high field, high temperature superconductors and liquid-metal first walls were derived independently of any computer simulation.

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## **#6- Axiom of Invariable Committee Approval**

*All review committees approve any proposal for any fusion energy concept.*

No fusion review committee ever saw a proposal it didn't like. The explanation can be found in the discussions for some of the previous axioms. Committee members assume that simplified theoretical behavior of any proposed fusion concept will not be thwarted by reality (see Axiom #1). They are generally ignorant of most practical reactor issues. They believe any cost estimate (see Axiom #4) and any computer simulation (Axiom #5) that's presented to them.

In MCF the very existence of committees to review non-tokamaks is a flouting of Axiom #3. But with appropriate assumptions, any fusion concept can be made to look viable on paper. And any computer simulation can be massaged to support viability (Axiom #5).

This unflinching endorsement by all review committees applies also to every proposed upgrade and add-on to fusion R&D installations.

The most important reason for universal endorsement is that review committees don't spend their own money, and they are happy to recommend that some other party fund the project. Approval should not be confused with actual funding, which is secured for only a fraction of proposals that are formally reviewed. Nevertheless, with their concepts sanctioned by review committees proponents have been able to launch dozens of fusion projects over the last half-century.

Examples are the host of aspiring fusion projects, mainly of the MIF type, recently funded by ARPA-E, the sporadic funding of discredited mirror machines, cusps and multipoles that have risen from the grave, and countless ignition test reactors and fusion engineering test reactors that were endorsed by review panels during the last 40 years but never implemented.

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### **#7- Axiom of the Infallible Concept**

*Despite dreadful experimental results, no proponent of any fusion concept will ever concede that it cannot be developed into a practical power reactor.*

Every proponent has fallen in love with his pet scheme, most people don't like to admit that they're wrong, and his or her particular approach is the only one the proponent knows how to do. The reasons cited for the failure of any program are that "the government (or investors) did not give us enough money, " or "the funding agency shut us down when we were on the eve of a major breakthrough." The proponent always claims that a larger (and more expensive) embodiment will cure all shortcomings.

**Double-Down Corollary:** *The asserted remedy for any experimental fusion device with appalling performance is to replace it with a much larger model of the same type.*

In most technologies, If an approach does not work, it is abandoned— the Darwinian-like process. But in fusion technology, no concept ever dies; failure means a bigger model must be constructed! Examples are theta pinches, mirror machines, and reverse-field configurations.

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### **#8- Axiom of Massive Electric Power Drain**

*Any fusion device and its auxiliary systems consume colossal amounts of electrical energy.*

One of the Achilles' heels of all types of fusion schemes— MCF, ICF or MTF— is the immense amount of electrical energy required to generate the high-temperature plasma on each pulse or "shot", as well as the large power required to maintain and control the hot plasma in the case of MCF [11, 12]. To minimize shock to the regional electrical grid, multi-GJ energy storage systems have been used since the 1960's to power fusion experiments.

Even when there is no plasma production, substantial *steady-state* electric power is required for essential auxiliary systems such as magnet cryogenics, vacuum pumping systems, water cooling systems and building HVAC. In the case of the ITER project, some 75 to 100 MWe (megawatts electric) will be consumed *continuously* by auxiliary systems, even when the plasma is dormant [11, 13]. Operation of ITER will be possible only because it is located at a site such as Cadarache, where there is access to many high-power grids. There are relatively few locations in the world offering comparable access to electrical power sources and water cooling resources.

While TFTR and JET demonstrated Q-values of 0.3 to 0.5 in the 1990's, inclusion of all the power drains of the site facilities (hundreds of megawatts, principally for magnetic coils) would have reduced the actual energy ratio to the order of 0.01. More recently, NIF has demonstrated Q-values exceeding 0.1, referring to energy absorbed by the fuel capsule, but the actual energy ratio would be reduced by a factor of at least 1,000 taking into account the electrical and wavelength conversion efficiencies of generating the laser radiation.

Hence the **Electrical Appliance Corollary**: *While effective fusion generators can turn electrical energy into neutron streams, they will never turn fusion neutrons into net electrical energy.*

Phoenix (Nuclear Labs) currently operates the fusion source that best exemplifies the appliance reality [6], with a fusion Q of 0.003, and an overall energy gain of about 0.001 including electric power to produce the ion beam, vacuum pumping and coolant pumping. This electrical appliance has many applications for the neutron output [14].

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### #9- The Tritium Deficit Axiom

*In situ* replenishment of all tritium burned and lost in any fusion device is impossible and will never be attempted.

The *in situ* replenishment of burned and lost tritium in any fusion device is a totally phantom enterprise that is likely to remain elusive forever. While the DEMOnstration reactor concepts always include replacement of *burned* tritium by breeding, they ignore the lost unburned tritium. In any case the DEMO's themselves will remain pure fantasy (see Axiom #11).

As long as there are no significant tritium breeding experiments in any fusion device, fusioners will confidently predict the ability to achieve global TBR > 1 with minimal extraction losses from the breeding blanket. Despite grandiose plans presented throughout the last half-century, no experiment to demonstrate *global* TBR > 1 will even be attempted for many decades, if ever.

Be that as it may, the heroic task of replacing burned tritium does not even address the most important issue of replenishment, because less than 10% of the injected fuel will actually be burned in MCF devices before it escapes the reacting region, although up to 30% burn-up may be possible in ICF systems. Of the vast majority of injected fuel that is not burned, 100% recovery is impossible because of trapping, implantation and permeation of reactor components as well as radioactive decay. When the burn-up rate is less than 10%, likely shortfalls in tritium recovery cannot be compensated by any practical breeding margin in the reactor blanket [12].

**Lifeblood Corollary.** *No tritium-fueled fusion generator is possible without a continual external tritium supply.*

Inescapable shortfalls in fuel recovery must be made up by tritium production in fission reactors at enormous expense. Supplying make-up fuel is economically viable only in quantities of 100 grams or less for modest tritium-burning applications such as producing neutrons for activation analysis, radiography or isotope production.

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#### #10- **Axiom of Untethered Promotion**

*The declaration of “breakthroughs” in fusion R&D is a continuous stream of laboratory and journalistic propaganda independent of any actual progress.*

Every result of experiment or computation from a fusion research institute, no matter how insignificant, is hailed with a press release and declared a “breakthrough.” Even *predictions* of hoped-for achievements are hailed as “breakthroughs.” Every trivial result in computer simulation is treated as a major advance that “will hasten the advent of unlimited fusion energy.”

In the period 2015-2020, proclamations by established labs and fusion “startups” of glorious but vague achievements together with great expectations reached an

unprecedented frenzy. As the propaganda and excitement about the fantasized imminence of fusion power reactors built up, actual progress as measured by improvements in the confinement triple product, or fusion neutron production, or Q approached zero for the more established fusion approaches, except for advances at NIF. For the “startup” fusion concepts, whether novel or resuscitated, the triple product and neutron production have remained so low as to be effectively zero. Across the board, practical work on relevant energy conversion technology, i.e., converting neutron barrages to electricity, has been non-existent throughout 70 years of R&D.

In actuality, “limitless propaganda” has replaced the prospect of “limitless energy”.

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### **#11- The Fanciful Roadmap Axiom**

*All “roadmaps” and “strategic plans” for fusion R&D are meaningless as soon as issued.*

A “roadmap” is a multi-decade schedule of tasks and milestones. The tasks listed in any roadmap or strategic plan for achieving a working power reactor may be essential, but the stated schedules are invariably nonsense.

Ignoring reality is the most important criterion in formulating a fusion energy roadmap. Any strategic plan must be untethered from reality. The reasons that fantasy is inherent in fusion roadmaps overlap those explaining Axiom Nos. 1 and 4.

In the period 1975 to 1985, detailed plans to implement numerous DEMO’s and engineering test reactors by 2000 were formulated in the USA, Europe and Japan. Those grandiose plans were abandoned by the year 2000.

In recent years, a second wave of DEMO concepts has been sweeping through Europe and Asia, at first calling for physical embodiment in the 2030’s, but soon pushed back to the 2040’s and 2050’s, in part to accommodate slippage in the ITER schedule.

The continual receding of imaginary construction dates for DEMO’s naturally follows from the Timespan Corollary to Axiom #1 and can be reformulated as a corollary of Axiom #11:

**Delusion Corollary.** *Implementing a demonstration or commercial fusion power reactor will always remain pure fantasy.*

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## #12- Axiom of Diversionary Claims

*Assertions of “doing good science” or producing valuable spinoffs are a sure sign that the fusion concept cannot advance.*

The US DOE-sponsored fusion program now comprises about 80% “doing good science” with unprecedentedly strong emphasis on computer simulation (see Axiom #5), sure signs of abandonment of any practical endpoint.

Suppose that the principals of a wartime project to develop an urgently needed revolutionary aircraft declared that their contraption could not fly, but they learned a great deal about aerodynamics. What would be the reaction of the funding agency?

Rarely there may actually be a technology spinoff from a particular approach to fusion energy, but in any case when proponents point to spinoff or science studies it means that it’s time for sponsors to abandon this fusion concept. A perfect recent example of a diversionary claim is TAE Tech’s proposed use of ion beams striking solid targets to produce neutrons for eradicating cancer tumors (a technique that is 8 decades old).

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## CONCLUDING REMARKS

Most of the axioms of fusion R&D manifest themes of psychology and sociology. Those subjects might seem alien to an enterprise that ought to involve only physical science and technology. However, all projects purporting to develop fusion power reactors comprise some mixture of foolishness, fantasy, delusion and fraud, decidedly human characteristics. Thus fusion R&D embraces behavioral science as well as physics and engineering. Fusion promoters have always used the artifices of psychology and sociology to ensure favorable news headlines and continued funding, and now that preoccupation has become even more critical as progress in advancing key fusion parameters has stagnated. Study of the axioms discussed herein will help fortify journalists, investors and funding agencies against the ever more preposterous assertions of the promoters of fanciful fusion reactors.

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