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The theory of the failure of magnetic fusion[1]

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Abstract

In the physics of the 20th century, fusion represents an extraordinary failure which eroded expectations of society on an "unexhaustible" energy source. The question is if these 50 years of research did really prove that fusion will be forever a "carrot" on a stick and always 35 years from its implementation.

When a person asks fusion people why this program is full of broken promises, the typical answer (besides conventional complaints on the lack of funding) is that the problem itself is the most difficult one that physics ever faced. In the FSU, such characterizations were done as early as in the 60s by Lev Artsimovich, the leader in the field.

This view is only partially applicable in the 21st century. Since the Artsimovich time, fusion, as a "difficult" problem, has been converted into the "complicated" one (around the late 80s). The presented theory makes a clear distinction between these two kinds of problems, which require significantly different management approaches, and explains the current stagnation in magnetic fusion by the lack of understanding this crucial difference.

The "difficult" problem self-organizes its own solution and does not require intervention of management. The state of the "difficult" problem is improving with time.

If an unresolvable issue was encountered, the "difficult" problem is converted into a "complicated" one. Without external intervention, the "thermal death" state of the "complicated" problem is getting only worse with time.

There is no natural way back from the "complicated" phase. Only an external "brute" force with "low entropy" means (computers, money, and sufficient intellect to make the problem "difficult" again) can reverse the situation.

Accordingly, it is not possible to expect that, without changing the management approach (or starting a new program), the hopelessly fragmented magnetic fusion would be capable to deliver the promised energy source.

Contents

1 Different faces of the 2nd law of thermodynamics.

The following statements have the same origin

Energy	*is not yet*	**Free energy**	*the only one which matters*
Data	*is not yet*	**Information**	*the only one which matters*
Data management	*is not yet*	**Creativity**	*the only one which matters*
Smartness	*is not yet*	***Intellect***	*the only one which matters*
Science	*is not yet*	**Progress**	*the only one which matters*
Expertise	*is not yet*	**Knowledge**	*the only one which matters*
References	*are not yet*	**Correlations**	*the only one which matters*
Monitoring	*is not yet*	**Leadership**	*the only one which matters*
Committees	*can not replace*	**Leaders**	*the only one which matter*
“Complicated”	*is different from*	**“Difficult”** *the*	*only one related to progress*

What is in “red” is a product of intellect or of more organized state. What is in “blue” is a background for “red”s.

With time the “red”s NATURALLY degrade into “blue”s

Recreation of the “red”s requires intervention of three “zero entropy” things: intellect, computers and money

2 The basics of research management theory

In programming, a typical problem is to match your understanding with control parameters of somebody's code

#	Control parameters user has in mind	FORTRAN namelist
0	promotion to AL	`igrid`
1	nomination to APS fellowship	`rleft`
2	major monetary award	`rright`
3	promotion within the rank	`zbotto`
	...	`ifcoil`
	...	`iecoil`
	...	...
	...	`fcturn`
95	minor disciplinary actions	`he`
96	suspension for a week	`ecid`
97	layoff	`vsid`
98	waterboarding torture	`rvs`
99	electric chair	`zvs`

In physics we match our knowledge with puzzles encoded by nature

2 The basics of research management theory (cont.)

The total number N_0 of possible sporadic matches of n (e.g., n=100) items in left and right columns is

$$N_0 = n! \quad (100\,!) \tag{2.1}$$

with an "entropy"-like quantity

$$S_0 \equiv \ln N_0 \simeq n(\ln n - 1) + \frac{1}{2}\ln(2\pi n) \tag{1}$$

There is similarity between number N of states in physical systems and their statistical properties with number N of choices in scientific research and statistical properties of its organization

Suppose some intellect is involved and both sides (physicists and nature) subdivide each set on n/k mutually consistent groups with k (e.g., k=10) elements in each

$$\underbrace{\ldots\ldots\ldots\ldots\ldots}_{n\ physics\ ideas} = \underbrace{\underbrace{\ldots A \ldots}_{k}\ \underbrace{\ldots B \ldots}_{k}\ \underbrace{\ldots}_{k}\ \cdots\ \underbrace{\ldots J \ldots}_{k}}_{n/k}$$
$$\underbrace{\ldots\ldots\ldots\ldots\ldots}_{n\ nature\ puzzles} = \underbrace{\underbrace{\ldots A \ldots}_{k}\ \underbrace{\ldots B \ldots}_{k}\ \underbrace{\ldots}_{k}\ \cdots\ \underbrace{\ldots J \ldots}_{k}}_{n/k} \qquad (2.2)$$

The job is reduced to matching k parameters inside each group

Organizing the job can be made in two ways, corresponding to logical '|' ('or') and '&' ('and') relations

Uncorrelated permutations ('|' choice) inside each section is the easiest way. The total number of actions N_1 in this case

$$N_1 = \underbrace{k!\,k!\,k!\ \ldots\ k!}_{n/k\ times} = (k!)^{\frac{n}{k}},$$
$$S_1 = \ln N_1 \simeq \frac{n}{k}(k\ln k - k) = n\,(\ln k - 1) \quad \simeq \quad S_0 \qquad (2.3)$$

Simple grouping of physicists (with no micro-management of the job) has a little effect on entropy of the system,

while being deceptively "efficient" for small n, k

As a rule, k and n rise in time (with n/k fixed) and initial "effect" disappears

$$S_1 = n\left(\ln n - \ln\frac{n}{k} - 1\right) \quad \rightarrow \quad n(\ln n - 1) \qquad (2.4)$$

"Organizing" job as uncorrelated "parallel" processes (in centers of "excellence") is a typical mistake in management

Imposing strong correlations ('&' type) is crucial for success

Matching sections in sequence reduces the number sporadic matches to N_2

$$N_2 = \underbrace{k! + k! \ldots + k!}_{n/k\ \text{times}} = (k!)^{\frac{n}{k}}, \qquad (2.5)$$
$$S_2 = \ln N_2 \simeq (k-1)\ln(k-1) + \ln n \quad \ll \quad S_0$$

Coherency in action results in dramatic reduction in entropy for any n.

```
{ Step0;
  { Step1;
    { Step10;
    }
    { Step11;
    }
  }
  { Step2;
  }
}
```

Coherency requires intellect. Mistake at the top cost a lot

Two types '&' and '|' of job organization have different properties

The type '|' ('or'),"organized" free research

1. Is inefficient
2. Results in further fragmentation of the job, rather than solving the problems
3. Has tendency to go out of control into "activity trap"
4. Is very stable

The type '&' ('and'), coherent with the global structure

1. Efficient in reaching the goal (if intellect involved).
2. Is metastable. Relies highly on competence and creativity of *Leaders*
3. Is prone to self-destruction as soon as unresolvable problem is faced.
4. Requires external control (inclusion into another type '&' structure).

An optimal mixture of a hierarchical structure with parallel groups can provide both stability and efficiency

A principle of "Two leg" structure may serve as an example

```
Box0;
  Box0a; /*necessary*/              |   Box0b; /*possible*/
  Projects                          |   Free research
    Box0aa; /*necessary*/ | Box0ab; /*possible*/
    Projects              | Free research
    ...                   | ...
```

Here, every level contains two kinds of jobs: **"necessary"** *and* **"possible"**.

The "strategically necessary" vertical line provides coherence
Its mission is to generate progress

The line "what is possible" provides stability

Progress (coherence) should NOT be expected from the free research

The natural tendency is eroding the **"necessary"** *into endless* **"possible"** *studies of, e.g., 45th type of ELMs.*

Management structure can be mapped to a C-code structure

```
Box0{
  BIGLEADER b0,b1,b2,b3; /* list of control parameters*/
  JobBox0();
   Box1{
    MIDDLELEADER a0,a1,a2;
    JobBox1();
    ------------------------------------------------------------
     Lab0[                |     Lab1[               |     Lab2[
      LEADER h0,h1,h2;    |     LEADER h0,h1,h2;    |     LEADER h0,h1,h2;
      JobLab0();          |     JobLab1();          |     JobLab2();
    ]                     |   ]                     |   ]
   -------------------------------------------------------------
    Box2{
     .......
    }
  }
}
```

This mapping makes the entire structure and its functionality transparent (and computer, not MS, controllable !!!)

Functional position of control parameters (or leaders) inside the structure is crucial

The typical structural a single element can be shown as

```
{
  LEADER  L0,L2,L3;   /* provide correlations across the parallel sections */
  [ CX_0 ] | [ CX_1 ] | [ CX_2 ] | [ CX_3 ] | [ CX_4 ] | [ CX_5 ]      (2.6)
  MONITOR  M0,M2,M3;  /* monitoring and selling the output */
}
```

It includes both "leaders" and "monitoring" control parameters. In management

"Leaders" are the meta-stable "inverse" population.

Their conversion into a very "stable" population of monitors is a NATURAL tendency

After loss of leaders the structural element falls into "activity trap"

Thermodynamically, the "activity trap" is similar to the thermal death of a "Heat bath", or "Thermostat" in physics

The thermostat in physics is characterized by:

1. *Large amount of total **thermal Energy** with no **Free energy***
2. *Equipartition distribution.*
3. *Destruction of any non-thermal fluctuation.*
4. *Ability to dissolve to non-existence any externally injected negative entropy (information) or attempts to generate a coherence.*
5. *Extreme stability: cannot be shaken, destroyed, or perturbed.*

Similarly, in the thermostatic scientific community

1. *Data collection and production of countless papers mimics progress.*
2. *Equipartition distribution of resources substitutes coherency*
3. *Emergence of **Leaders** is impossible*
4. *Only external achievements are recognized (like in PPPL was with spherical tokamaks and quasi-symmetry ideas), while internal ones are ignored.*
5. *The attempts to impose correlations are confronted by entire community*

Funding the thermostatic community is the same as to boil water with the green laser beam

3 “Difficult” and “Complicated” problems

Everybody likes Difficult problems. Needs no management

*The **Difficult** problem is one which opens a way to something never seen before. Such a problem is typically localized and pretty well formulated.*

*A **Difficult** problem excites the bright minds and **self-organizes** its own solution. The funding and managing of this kind of problem is relatively straightforward. Everybody feels himself as a leader.*

In fusion, the phase of a “difficult” problem was passed through essentially in the 50s-70s when the foundation of high-temperature plasma physics was created. At that time, the basic theory was formulated, the most promising magnetic configurations (tokamaks and stellarators) had been identified, and the neutral beam injection was introduced as the most efficient heating method, capable of providing the reactor level of plasma temperature in tokamaks.

All of this had a big impact on expansion of fusion research in 70s-80s. But the success and achievements at that time were not sufficient to meet the power reactor requirements.

With initiation of the ITER project in 1985 the reactor issues (related to 14 MeV fusion neutrons) were faced at the conceptual level.

At this moment the golden age of magnetic fusion was over

(It was 2 orders of magnitude away from generating the relevant level of neutron fluence)

3 “Difficult” and “Complicated” problems (cont.)

Complicated problem is a nightmare for everybody

*In the case of such problems, the issues are distributed over numerous areas of expertise. In contrast to the **Difficult** one, the **Complicated** problem requires not as “bright”, but “right” minds (intellect rather than smartness).*

Instead of expertise in a narrow field, it requires coherence of researches of different nature and the cross-discipline knowledge.

Leadership** with a science based strategic vision, which is capable of synchronizing the developments across different interlaced areas, make them mutually consistent, and lead to resolving the problems, rather than moving them into an indefinite future, **becomes a crucial need

In a Complicated problem, there is no such thing as “self-organization”. Without capable leadership, the research is unavoidably pushed into endless fragmentation

The result of self-evolving complicated problem is stagnation

The thermodynamic process destroys the remains of long range correlations in research. Mutual understanding between adjacent fields is replaced by citations and references. The strategic vision is totally lost in petabytes of “data” coming from uncorrelated research.

The knowledge of Leaders is always confronted by “expertise” of individual scientists

The same thermodynamic process destroys the remains of the previously available (if any) structure of scientific leadership.

The unspoken goal of a “complicated” program is in preserving the most comfortable, unperturbed, never ending “thermal death” state, rather than in making progress. Special resources are allocated for propaganda in order to make impression for the society that the research is still promising.

Equipartition distribution is the overwhelming principle of functionality of a Complicated program

Reconstitution of structure of leadership is necessary (although not sufficient) for dealing with stagnation

Because of the nature of the mentioned physics law, the only reasonable administrative approach to the complicated problems is to use the power of money for preserving and watching the functionality and reproduction of the scientific leadership structure by motivating young, knowledgeable people to the top leadership positions and rotating them.

The force should be applied if the scientific community resists the promotion of stars

*Scientists are interested in “understanding” things are motivated by their own recognition. The **Leaders** are interested in making progress.*

The criterion of distinguishing a scientific leader is very simple.

The Leader is able to see the information behind the scientific data and use this information for making progress.

Only scientists who made tangible contribution to the progress are capable to lead the program. The inferiority complex and leadership are mutually exclusive. Combining them leads to a disaster.

The structure of leadership is fragile and can be lost unnoticeably

In making progress it is not possible to rely only on Leaders

The price of mistakes of scientific leaders is always substantial.

*In order to make progress robust, if is necessary to balance the **Leadership** structure with a relevant **"free" research**, which is driven by people abilities. E.g., in Kurchatov, an explicit scientific policy was*

"We are doing everything necessary for atomic industry, and then whatever is interesting to our people".

*In a balanced program the **Leadership** is providing progress, while the **free research** provides the stability.*

*In a **Complicated** problem, **free research** is prone to fragmentation and stagnation. Easily recoverable, **free research** should not be allowed to erode the pace of progress.*

The tendency of free research to fall into fragmentation should be recognized and constrained by supervision from the top

Every bureaucrat knows the importance of hierarchy for problem solving

In practice this understanding is typically reduced to necessity of a management structure which should efficiently distribute the money.

*Incapable to do this by itself, but assuming the role of a **Leader**, the bureaucratic management relies on arbitrarily chosen scientists elevated to the level of different kind of advisers, project leaders, evaluators, etc, neglecting the simple criterion of **Leadership**.*

In fact, a typical scientist is skillful in a localized area of expertise. He will always miss the important information, as soon as it falls outside his narrow knowledge or activity.

The real role of bureaucratic management is to use the power of money in order to maintain and reproduce the leadership structure

In this regard, the structure of a scientific leadership is a subordinate of the management structure, which does not intervene into scientific policy as soon as progress is provided.

The natural tendencies gradually convert leaders into monitors without explicit destruction of structure

Instead of leading the research, the monitors are collecting the results on the ongoing research and arranging its output. In fact, they are soon become unqualified even for such a simple task, and put the burden on the active scientists.

If started from the top of the structure, the degradation prolongates down the structure as a chain reaction. Incompetence at the top cannot coexist with the leaders at low levels and uses all means to suppress them. Vice versa, erosion at the low levels paralyzes efforts of the top leaders.

*Natural processes in **Complicated** problem are replacing the structure of **Leadership** by a dysfunctional structure of **monitoring**.*

***Monitors** are inherently intolerant to any indication of **Leadership** or independence.*

*Another way of erosion is substitution of dysfunctional structure of leadership by a "collective" rule of countless **Committees**.*

With no real responsibilities, the Committee members are preserving equipartition distribution of resources and stagnation rather than motivating progress.

Preserving the scientific Leadership requires intellect of management

Slipping toward stagnation (or activity trap) does not require any efforts. It happens by itself.

*Then, no one realistic budget can cure the deadlock situation, typical for a **Complicated** problem. Any budget will be consumed with no tangible results. It is meaningless to mix money (the low entropy substance) with a scientific program already reached its highest entropy state (fragmentation or stagnation). The **Complicated** program is a sort of welfare system with no hopes for return.*

When control is lost, the scientific approach would be to spend extra money and launch a new, smaller program, which should be put back to its "difficult" phase by focusing it on specific, rather than general science objectives.

New program can absorb creative elements from the old one, letting it naturally evolve to further stagnation and disappearance.

The simplistic approach of cutting funds does not reach its goal.

It does not touch "deadwood" and incapable management, but hurts young and creative people.

4 Deadlocking of fusion

Deadlocking of fusion was manifested by inability of ITER project to address nuclear aspects of reactor in the late 80s

The fusion program of the last decade is a perfect example where every earlier explained rule was violated. Instead of recognizing the destructive role of natural tendencies in fragmentation of research and degradation of leadership, OFES demonstrated its inability in keeping the pace of progress.

All its action eventually assisted deadlocking, e.g.,

1. *Transition from the "difficult" to "complicated" phase was not recognized.*
2. *The structure of leadership was not protected. It has disappeared.*
3. *Fragmentation of the program was legitimized and assisted.*
4. *Experimental base of the program was severely damaged.*
5. *Monitors contaminated the entire structure of management.*
6. *Suppression of new ideas was officially arranged by confronting the science by majority opinion.*

[redacted]

4 Deadlocking of fusion (cont.)

Conversion of the US fusion from energy into the "science" program in the mid 90s accelerated its transition into the hopeless "Complicated" phase

Discovery of Quiescent H-Mode on DIII-D and then the unshakable (by RMP) temperature edge pedestal were the only exceptions manifesting a progress in magnetic fusion during the last 8 years.

LiWall Fusion concept was a development by a few separated from "activity trap", which overflowed with turbulence studies and noise in numerical codes and in scientific media

Not a surprise for the complicated phase, that for 8 years most of members of the so-called "Theory" Department in PPPL cannot accept the uncertified by R.Goldston or R.Hawryluk "heresy" that the edge plasma temperature can be comparable with its core value.

4.1 PPPL in the 21st century with a plasma from the early 70s

This section not exposed because of obvious reasons

The criterion of conceptual relevance to reactor R&D is very simple: ability of delivering

15 MWa/m^2

of neutron fluence,

or burn-up of

1 kg(T)/m^2(FW)

A compact Reactor Development Facility (RDF) with new plasma regimes is absolutely necessary

(ITER is capable of only 0.3-0.4 MWa/m^2 (burn-up of 10-15 kg of T, instead of 650 kg)

The official fusion “strategy” ignores both science and reality.

All conceptual reactor ideas of official fusion look ridiculous when compared with, e.g., the LiWall Fusion (LiWF) concept

Issue	LiWF	BBBL70* concept of “fusion”
The target	RDF as a tool for reactor designing	Political “burning” plasma
Operational point:	$P_{NBI} = E/\tau_E$	ignition criterion $f_{pk} p \tau_E = 1$
Hot-α, 3.5 MeV	”let them go as they want”	“confine them”
Cold He ash	residual, flashed out by core fueling	“politely expect it to disappear”
$P_\alpha = 1/5 P_{DT}$	goes to walls, Li jets	dumped to SOL
Power extraction from SOL	conventional technology for $\frac{\tau_E^*}{\tau_E} P_\alpha$	no idea except to radiate 90 % of P_α by impurities
Plasma heating	“hot-ion” mode: NBI $\rightarrow i \rightarrow e$	first heat useless electrons: $\alpha \rightarrow e \rightarrow i$
Use of plasma volume	100 %	25-30 %
Tritium control	pumping by Li	tritium in all channels and in dust
Tritium burn-up	10%	fundamentally limited to 2-3 %
Plasma contamination	kill the Z^2 thermo-force, clean plasma by core fueling	invites all “junk” from the walls to the plasma core
He pumping	Li jets, as ionized gas, $p_{in} < p_{out}$	gas dynamic, $p_{in} > p_{out}$
Fusion producing β_{DT}	$\beta_{DT} > 0.5\beta$	diluted: $\beta_{DT} < 0.5\beta$
		* stands for the “Bib$_b$le of the 70s”

As a reactor concept, the BBBL70 is inconsistent with common sense

Even at scientific level the BBBL70 is not scientific

Issue	LiWF	BBBL70 concept of “fusion”
Physics:		
Confinement	diffusive, RTM≡ χ=$\chi_e = D = \chi_i^{neo}$	turbulent thermo-conduction
Anomalous electrons	play no role	is in unbreakable 40 years old marriage with anomalies
Transport database	scalable by RTM (Reference Transp. Model)	religious beliefs on applicability of scalings to “hot e”-mode
Sawteeth, IREs	absent	unpredictable and inavoidable
ELMs, $n_{Greenwald}$-limit	absent	intrinsic for low T_{edge}
p'_{edge} control	by RMP through n_{edge}	through T_{edge} and reduced performance
Fueling	existing NBI technology	no clean idea yet
Fusion power control	existing NBI technology	no clean idea yet
Operational DT regime	identical to DD	needs fusion DT power for its development
Time scale for RDF:	$\Delta t \simeq 15$ years	$\Delta t \simeq \infty$
Cost:	$\simeq$ $2-2.5 B for RDF program	$\simeq$ $20 B with no RDF strategy

LiWF suggests a way for bootstraping its funding

Official fusion is wastful and already compromized the idea of fusion

5 When will fusion provide electricity ?

Only FESAC knows for sure that this will happen in 35 years
(following the question)

Meanwhile, it is naive to expect that fusion will make a “self-organized” backward transition from its well developed thermal death phase of a ***Complicated*** *problem into a golden age when it was* ***Difficult****.*

No way. Without understanding the basic tendencies in research and making the management scientific and realistic, it is impossible to reverse degradation.

The present theory suggests a practical approach in combining what is ***“necessary”*** *with what is* ***“possible”****.*

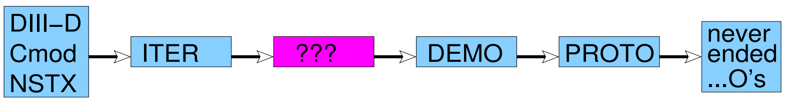
The LiWF concept was created in compliance with the ***necessities*** *of magnetic fusion strategy. It should be given a status of the* ***“first leg”*** *on the way to reactor development in the US. ITER implements only what is* ***“possible”*** *and can serve as a second, research-stabilizing leg.*

At least in theory, implementation of this management approach requires initiation of a new program, rather than vitalizing the present one

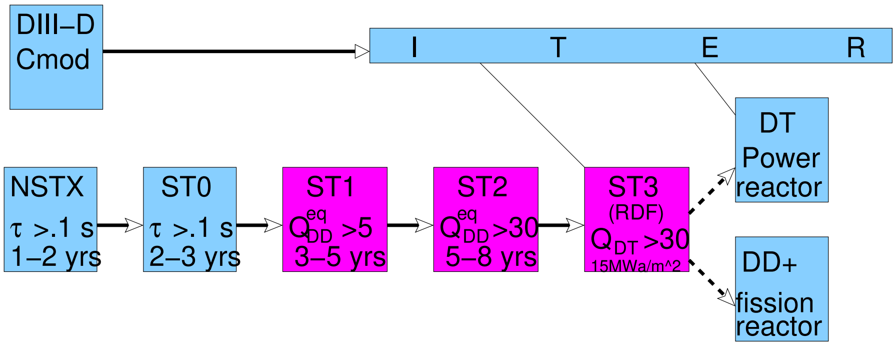
6 The Orbach/Bodman (DoE) initiative

The Orbach charge (Feb. 2007) can be interpreted

as another chance to ignore the basics of strategy and follow the old teaching



or as an opportunity to develop the LiWall plasma regimes for RDF on the time scale competitive with ITER



LiWF strategy does not need fusion power (“burning plasma”) until its last step 3 (ST3)