*A rebuttal prepared by the French Commission of Atomic and Alternative Energies in reply to an article entitled "ITER: Chronicle of an Inevitable Failure" published by Mr. Jean-Pierre Petit in the November 12th issue of the review, **Nexus***

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Introduction

Mr. J.P. Petit, a member of the French Anti-Nuclear Association, "Ridding Ourselves of the Nuclear Option" has published an article in which he hotly contests the ITER project by stirring up unreasonable fears. His line of reasoning is primarily based on a series of excerpts, taken out of context, from a doctoral thesis that was recently written at the Institute of Research on Fusion through Magnetic Confinement at the CEA. It was formally defended in November 2010 at the Doctorate School of the "Ecole Polytechnique" and deals with the specific question of the phenomenon of disruptions that are likely to occur during the operation of ITER. A disruption, a phenomenon well-known for quite some time is an instability that may develop within the Tokamak plasma. Loaded with a high amount of energy, it leads to a rupture in the magnetic confinement and results in a highly intense electrical discharge towards the wall of the confinement vessel with a risk of damaging it. This highly reputable thesis is based on 50 years of work carried out by members of the worldwide scientific community involving several thousand professionals and constitutes the recognised basis of the current scientific debate about this subject. There is abundant literature on the subject of disruptions, particularly in articles that are regularly published in the Nuclear Fusion Journal. They make up both the official and public physical basis in the design of ITER. In observing that Mr. J.P. Petit's article deliberately chooses only to take into account excerpts selected from the work that correctly confirm the attention that the scientific community must devote to the phenomena of disruptions, we can only conclude that his specific purpose was to provoke a political polemic with malicious intent. Certainly no substantial scientific work of genuine quality was carried out in a spirit of constructive criticism that might have been destined to provide fresh knowledge of the subject. We are distressed in witnessing the lack of thought with which the scientific information itself, published in reviews of international renown, their authors but also the readers of the article have been manipulated for partisan ends wholly foreign to research and the progress of knowledge. By indulging in such intellectually dishonest behaviour, Mr. J. P. Petit has, ipso facto, disqualified himself from the debate whether it be of a scientific or social nature.

The purpose of the present document is to refute the most shockingly incorrect points that have surfaced in Mr. J.P. Petit's analysis as much from the scientific standpoint as from the view of his lack of knowledge about the general contact of the research and furthermore to provide the reader with the major keys in reading this same context and the precise role that ITER must play in the pursuit of magnetic fusion in the decades to come.

An analysis of Mr J.P. Petit's criticism

The major argument that Mr. J.P. Petit has put forward is that ITER would never be able to withstand the disruptions, a phenomenon that would lead to a quick shutdown of the plasma. Let's analyze point by point the criticism levelled in the article (the excerpts are printed in italics)

page 91 "After reading this, we conclude that fusion through magnetic confinement and the physics of tokamaks, extremely complex, have in no way whatsoever been mastered by it theorists. Positively no modelling of the plasma behaviour contained in these machines is representative in that it is and shall remain for a very long time impossible to manage, even by using the most *powerful supercalculators in the world, a problem involving 10^20 à 10^22 electrically charged particles interacting with one another."*

Such remarks are genuinely surprising, coming from someone who claims to be "a highly experienced specialist in the field of plasma physics" No examples are lacking in the theories and models operating quite well on a great number of particles. It turns out that Magneto-Hydrodynamics (MHD) is a scientific discipline that can describe the dynamics of plasma or a conducting fluid having a great amount of particles. The computation power presently available even allows us to carry out simulations in their actual dimensions. Unless we wish to question the work of the scientific community itself—a community to which he has belonged for more than 20 years, Mr. JP Petit cannot seriously defend his assertion in which he states that it is impossible to simulate a dynamic system having a great amount of particles.

This said, nobody has claimed that tokamaks were and must be designed on the basis of numerical simulations. In practice, the technical specifications of a tokamak concern their resistance to disruptions based on "scaling laws" called "engineering laws" that deal with the energies and characteristic times brought into play in this process. The values chosen for ITER have been validated by experiments carried out on a great number of tokamaks over more than half a century. The numerical simulations of disruptions only appeared recently, particularly in the thesis of M. C. Reux to whom Mr. J. P. Petit had devoted such exaggerated attention. In fact, the results are quite encouraging, even if their accuracy could still stand some improvement. It is only fitting to point out once again that these simulations constitute an additional refinement in our comprehension of tokamak plasmas and not the basis of the ITER design, validated long ago by the "engineering laws" mentioned earlier.

p. 91 "All the tokamaks in the world including Tore Supra and JET have become ungovernable under the effect of extremely varying causes"

This assertion is obviously erroneous and totally untrue: Tore Supra and JET have been performing in a completely satisfactory and perfectly safe manner since 1988 and 1983, respectively. In other words, more than 20 years of successful operation for Tore Supra and almost 30 years for JET. Disruptions regularly occur in these two machines (as in all the others) but they have never led to the destruction or to a loss of containment of toxic products such as it has been envisioned in the fantasy scenario of Mr. Petit. 30 years of operation with no major incident is certainly not what one could honestly call an "ungovernable" situation!

p. 92: "the disruptions …spawn forces that are capable of distorting the parietal structures into wisps of straw"

The elements of the first wall and structure of the Tokamak and particularly that of ITER have, of course, been designed to withstand the forces produced by disruptions including the most powerful ones imaginable. These elements are put together in order to minimize the electrical currents that circulate during a disruption, thereby limiting the tensile forces that they might undergo. Furthermore, in extreme cases causing superficial damage to these elements, the latter have been designed to be replaced. The photograph shown in the article and taken from the thesis (a damaged element from Tore Supra due to the effect of a disruption) is in this respect truly exemplary: it shows us a "finger" (an element from the first wall) twisted in Tore Supra owing to the effect a disruption. It has been replaced, the electrical current paths have been corrected and Tore Supra has been in perfectly normal operation since then! It is certain that during ITER'S progressive commissioning phase, situations like this will arise and the observed flaws will be corrected, just as it happens in industrial or research facilities in their initial operation period (cf. the situation of CERN in 2009). Obviously, the machine will be tested with currents lower than the nominal value in order to minimise potential degradations during this initial adjustment phase.

p.93:" lightening produced there will inevitably reach 15 million Amperes (150 million amperes on its successor DEMO). Impacts of such power will perforate the vacuum vessel. The Beryllium layer …will vanish and disperse the materials it is made of--- along with the tritium at the same time--- which is radiotoxic and confined in the chamber"

This assertion is doubly false. Even if we were to suppose that in such an extreme situation, a perforation of the vacuum vessel occurred in ITER following a disruption, there would be no Beryllium release or Tritium outside of the facility. The vacuum chamber is surrounded by a series of containment barriers that will not be affected by disruptions. In addition to this, DEMO will certainly not operate at 150 MA but at currents on the order of those in ITER (15-20 MA). The sloppy and peremptory extrapolations of Mr. Petit clearly demonstrate his profound ignorance of physics and tokamak technology.

p. 93:" the Laplace forces, which are in the thousands of tons, could distort the structures of the machine, necessitating their replacement, indeed a complete overhaul of the entire facility".

Measuring the forces in tons is even more surprising when it is done by a person who claims to be a physicist. A force is measured in Newtons and mass in grams or tons. The Laplace forces induced by ITER are estimated to be capable of reaching billions of Newtons. The ITER structure elements are designed to withstand these several billions of Newtons-therefore it shall not be necessary in any case imaginable, to replace them. For 30 years, JET has withstood disruptions leading to forces of several billion Newtons. The facility was built to withstand such forces without undergoing any distortion.

p.94: "There is absolutely no means whatsoever to extrapolate and re-use the existing data …these incidents, inevitable at the time of the implementation, will lead to the destruction of ITER as soon as the initial tests are launched"

Such sweeping assertions are erroneous. There are indeed means and codes highly reliable in estimating the currents termed, "halo" that are linked to a disruption, the level of asymmetry in these currents in a toroïdal direction, as well as the forces exerted in the vacuum chamber. This estimate is consolidated in a database ("the ITER disruption database") completed by observations made in a great number of tokamaks of varying sizes. As it was mentioned earlier, there are numerical MHD simulations constantly proving to be more accurate thereby enabling us to independently estimate and highly refine the nature of disruptions but these have not been used to design ITER because the decisions taken were prior to the development of the simulation techniques. The simulation techniques are now used for the purpose of enhancing our comprehension, verifying and helping in the definition of the commissioning tests, in the design of all the forthcoming experiments and in the use of their results. Let us mention once again, that the ITER commissioning tests will be carried out using reduced plasma current (just like any other machine) with a progressive power increase and therefore in situations involving no risk to the integrity of the machine.

p.94: "the hope that one day a tokamak can operate with no disruption is as senseless as imagining the sun with no solar disruptions, a weather report exempt of any wind or snow or cooking oneself a casserole filled with boiling water that produces no flurry"

A tokamak may function with no risk of disruption if the plasma is stable vis à vis the MHD modes. De facto, these are the normal operating conditions in the majority of tokamaks and ITER will not escape this rule. One must be careful not to confuse instability and turbulence. A disruption is due to a perfectly determinist instability. If the plasma is stable in confronting this instability, there is no reason whatsoever that it might occur owing to the reproducibility of determinist physics. This very important point was confirmed by the analysis of the ITER database previously mentioned: there is no random character in the triggering of a disruption even if the physics involved are complex. Turbulence (the image of our casserole) is associated with a multiplicity of instabilities on a small scale. In actual fact, turbulence is chaotic. It is unavoidable but does not lead to a disruption. A disruption can enter a state of turbulent operating conditions but afterward only, once the primary instability is set off. On this particular point, the figure shown in the guise of an illustration by Mr. Petit is irrelevant: it represents a turbulence that has nothing to do with a disruption.

Obviously, one of ITER's objectives is to perfect a scenario stable with regard to these disruptions. Once the scenario has been found, there will be positively no reason for it to become disruptive spontaneously.

p.95: "disruptions can damage any of the elements of a tokamak including it supra-conductor system of magnetisation and it must be recalled that it contains the same energy as that of the Charles de Gaulle aircraft carrier launched at a speed of 150km/h"

This assertion is once again false. The vacuum chamber will be protected by a blanket in charge of stopping the 14 MeV neutrons resulting from fusion reactions and even more so the fast electrons issued from the disruptions and that will not succeed therefore in approaching the magnet. Let us repeat yet again that the structure elements which include the supraconductor are designed to withstand a disruption. The energy brought into play at the time of a disruption has nothing to do with the energy of a toroidal magnet. On the contrary, it is rather a question of energy content in the plasma (approximately 350 Mega Joules for an ITER plasma at full power) and the energy of the magnetic field, termed poloidal (about 400MJ)—the two not being released at the same time—therefore are not commensurate with the 51 Giga Joules mentioned or for that matter with any aircraft carrier launched at 150km/h whether we are talking about the *Charles de Gaulle* or another carrier.

p.95: "if we wish of offer an image of the implementation of a tokamak, we should have to imagine a machinist standing in front of a boiler and a few measuring instruments. If one of the needles registers the slightest tremor and begins shaking, his only possible course of action is to drown the fire pit by using a fire hose."

Once again, we witness his ignorance of what a tokamak actually is and a manipulation of the facts for the purpose of partisan ends. Tore Supra is equipped with 40 measurement instruments working on a continuous basis. JET has about 80 and ITER will have even more. To speak about "a few measurement instruments" is, in the least, conveniently minimal. As for the "fire hose", the estimate of the available time to stop or slow down the fast electrons is about 10 ms. It has been estimated that it would be necessary to inject 10^{22} electrons per cubic meter for a "gradual" shutdown (cf. the reference document "ITER Physics Basis" which describes the physical design basis of ITER, published in *Nuclear Fusion* and co-signed by the entire world community). This is not an impossible task! As a matter of fact, the study of massive gas injection as a means of stopping the fast electrons is precisely the subject of Mr. C. Reux's thesis. Other techniques are under study by several scientific teams throughout the world, one of which is at the CEA for the purpose of selecting the option that displays the best performance at the most reasonable price. The present results are encouraging and we might reasonably suppose that one or perhaps even several of these innovative methods, apart from the one that is already available, will be perfected between 2019 and 2020 for the initial hydrogen plasma and especially in 2026 for the first deuterium-tritium plasma.

p95: "It is most surprising that the nuclear safety authority has never mentioned this highly dangerous state..."

This proves that his knowledge of just exactly who the nuclear safety authorities are among the 7 partners of ITER is sadly deficient. (Japan, South Korea, India, China, the United States of America, the Russian Federation and the European Union). With regard to the French, it is hard to believe that for a single instant they could have never made mention of this if these disruptions were as dangerous as Mr. Petit seems to imagine in his wild fantasies. His malevolent sentence aims at making one believe that the disruptions have been deliberately hidden from the various decision-making authorities in their assessments. Nothing could be farther from the truth. The disruptions have been widely discussed in the literature. In fact, more than 35 pages are devoted to them alone in the "ITER Physics Basis", published in the journal of *Nuclear Fusion* in 2007 (completing the initial 1999 report). The number of international publications dealing with this subject amounts to the hundreds. Insinuating that the subject was deliberately eluded, indeed hidden, is simply the opposite of the truth. What is surprising is that Mr. J.P. Petit, who proclaims his scientific manner of proceeding in his search for the truth, had based his peremptory assertions essentially on a very superficial reading of the work carried out in Mr. Reux's thesis and loftily ignores the thousands of pages devoted to the very subject concerning the disruptions in scientific reviews of international renown. We can only be surprised at his surprise!

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Having exposed the excessiveness of Mr. Petit's remarks, we now feel that it is only fair to answer his legitimate questions concerning the opinion of the ITER research project in the form of a synthesis namely, "what precisely is going on in the operation of the Tokamak ITER and its situation with regard to the disruptions?"

Magnetic fusion research and the role of ITER

Nuclear fusion research, by means of magnetic containment, is a type of research termed "societal". This means that it is striving to mobilize, in a manner as coherent as possible, an entire community of people who possess various scientific and technical competences. All of them are working towards a common goal, namely, the development, in optimal safety conditions, of a source of energy based on the principle of the fusion of two light nuclei. Mr. Petit in his introduction reminds us in the form of a very brief summary that we may now speak about the domesticating on earth of fusion energy, this energy produced by the stars and in particular by the Sun.
It is a task of great magnitude indeed that we have now chosen to tackle! This challenge, for it is one of significant dimensions, consists in first verifying if such reactions are possible on Earth and if so--are they of human dimensions? The good news is that a tangible and remarkable result produced by the scientific community has proven that it is indeed possible to find a point of operation for this nuclear fusion reaction that is compatible with "human" realisation. In clearer terms, the dimensioning of the physics that it calls on indicates that a reactor of this type can be envisioned in industrial facilities comparable to those we already are familiar with in the massive production of electricity. This is a decisive stage in the pursuit of this research. This stage was reached at the end of the 1990's particularly by an experimental demonstration in the European tokamak, JET that was universally recognised. It ended a long but decisive phase in the history of fusion now known as "the pioneering phase".

Several books specializing in this particular subject have already been written about this phase in the history of fusion, but it is important to point out the major conclusions that must be translated into accessible terms for the general public and to people interested in our choice of societies. This pioneering phase is typically divided into two periods, the first period covers two decades between the "declassification" of the research (1958) and the decision to build JET (1980); the second period spans the two following decades that have been marked by the operation of the great tokamaks, the biggest of which still today is JET. The works usually ended with the collective decision to undertake the construction of ITER (2005). In the first period, many different ways were explored throughout the world in a highly competitive spirit to develop what we call the magnetic configuration, namely the immaterial "box" the purpose of which would be to confine this extremely hot plasma. Everyone understood that no material wall could possibly contain it. The configuration that won hands down in this competition was the tokamak configuration, offered by Russian researchers and ever since then its design has not been disputed. Other configurations were simply ruled out but several alternative options have been kept and examined and they are still under consideration today. If the tokamak configuration won out and is presently at the top of our list, that doesn't mean that it is perfect or even the ideal model. The second period consisted in identifying the performances of the tokamak configuration, which means that we were seeking to establish the "engineering laws" that would enable us to extrapolate the acquired results for the purpose of designing a reactor. It is of capital importance here to understand that, as in any industrial process, drawing up the "engineering laws" does not necessitate a complete comprehension of the underlying physics involved in the phenomenon. For example, this is what happened in the field of aeronautics: our airplanes have been flying for more than 100 years, our missiles have been going to the moon for more than 40 years, but the turbulence physics around the wing of an airplane, if it is understood overall, has still not been entirely "solved" and thus remains an object of research. Our first automobiles were developed and commercialised by people who did not master the thermodynamics of the gas explosion engine in all its complexity. The normal procedure in this type of research is always to combine experimental information (i.e. we build prototypes, we make them work, we measure the study parameters and we analyse our findings to model the system in operation and thereby master it) with theoretical information (here, we explore the physical processes that rule the phenomenon, we ask questions, we find the answers to them, and we compare them with the results obtained from the experiment), combined with engineering models that reproduce the behaviour in an ad-hoc manner and which, in general, are simple laws with parameters adjusted to the experiment. So in this respect it must be recalled that the purpose of such research is not simply knowledge for knowledge's sake but rather the development of a specific type of knowledge required to meet a specific need and which therefore demands the perfecting of some type of equipment or innovative process integrating all sorts of knowledge and know-how. It is the constant iteration between these activities that enables us to move in steady progression towards the desired result. At this particular stage, Monsieur Petit has lumped his whole analysis together and if it is true that the physics of plasma have yet to be completely understood in their most fundamental aspects, it is absolutely false to assert that this knowledge is a pre-requisite to the proper functioning of ITER. It is a little hasty to ignore or envision in some naïve manner the complete process which underlies all applied research. On the other hand, it is obvious that the scientific fusion community has not in any way given up its efforts in tirelessly pursuing an absolute, in-depth comprehension of the subject because such knowledge provides the ultimate key to the optimisation of this process. Developments of simulation brought up to new, improved international levels, the massive use of the most advanced calculation means clearly demonstrate this concern should there be any need to prove it. The French nation can pride itself in being the world leader in certain areas of research including that of turbulent processes that govern the confinement laws of the plasma, the key to its performance, and the non-linear magneto-hydro-dynamics (MHD) which govern the stability of this same plasma. Monsieur Petit, who claims to be a former expert of MHD himself, can hardly claim not to be aware of the considerable progress made in MHD simulations of tokamak plasma, some of which were conducted by Mr. Cédric Reux in his thesis which is so generously cited by Mr. Petit himself.

So where is ITER at this point and what is its exact role?

If there is one highly persistent idea that will not go away when speaking about ITER it is the one that links this complex project of highly imposing dimensions to the end of the story. Before asking ourselves the question: "What is ITER?" we must first understand what it is not. ITER is not a fusion reactor, nor does it serve any commercial purpose or act as a prototype. On the other hand, ITER is a highly refined research machine, the product of a collective and comprehensive synthesis of the results found by its pioneers who, may we recall once again, validated the scientific feasibility of magnetic fusion. This work could have concluded, for example, that the physics demanded a "machine" some 100 meters in diameter or a magnetic field incompatible with what was physically imaginable. However, such was not the case and it was indeed these scaling laws developed and tested with adequate and quite rigorous scientific discipline that allowed us to assert this. The JET results at the end of the 1990's in fact confirmed that by using the deuterium and tritium mix, we could indeed obtain what had been extrapolated from the results obtained using pure deuterium. Mr. Petit is right when he says that the presence of tritium is indispensible to the production of the fusion reaction but he is wrong when he insinuates that tritium is not used because it is expensive or "dangerous". There was no valid reason whatsoever to carry out all the developments and tests with tritium on JET while knowing how to extrapolate the behaviour of fusion plasma based on deuterium plasma (and in this case, based on the great principles of quantum mechanics). The question of tritium can be essentially separated from the rest of the physics question and its presence only becomes necessary when we move on to the "actual size" aspect which is one of the major roles of ITER. Since the 1990's, scientists have attributed specific scientific missions to ITER that are linked with questions that we hope to answer or extrapolations that we hope to confirm because it will be the first time we are able to obtain these result in a machine on an authentic scale. These scientific missions essentially fall into three categories:

- Production of plasmas of deuterium and tritium which will cause the energy released from the reaction to dominate the necessary energy for maintaining the process. We have set at a factor of 10 the desired amplification between the power injected to trigger the reaction and the retrieved power within the plasma. In order to obtain this major result, ITER will have to not only confirm that the extrapolations are correct but also contribute to providing the major results about the behaviour of such plasma concerning confinement and stability.
- Production of plasmas of deuterium and tritium which will cause the energy released from the reaction to contribute significantly to the maintenance of the process and even more so in the length of time conditions prefiguring the reactor operation, i.e. approaching what we call, "stationary". This second condition demands extra constraints of generation of the plasma current itself through additional power systems.
- Finally the testing of conditions close to what is called ignition, meaning conditions in which we try to minimise the total injected power so that we can determine the point of operation in a future reactor.

Along with the scientific mission assigned above to ITER, ITER also marks the beginning of a new era in fusion in that it must also demonstrate the technological feasibility of the process. In plain terms this means that ITER must demonstrate in the long run that magnetic fusion is or is not a process that can lead to a nuclear reactor type totally different from those presently in existence. This challenge is taken with the greatest amount of seriousness by all people involved who are playing their respective roles. The ITER team is responsible for offering a machine which must, in the long term, complete this mission as well as propose experimental protocols that, one by one, will be validated by the Nuclear Safety Authority before any commissioning and any introduction of tritium into the machine. As we have stated above, ITER can operate and in fact will operate, without tritium until all these stages have been validated. This is the major reason why the experimental ITER plans at the present time anywhere between 5 to 7 years of operation before the introduction of tritium. Afterwards, ITER will proceed by stages with tritium up to the performances scheduled for it. At the time of this process, all components and physical processes will be once again tested, modelled and compared to the predictions thereby continuing the progression of the process but this time in an integrated manner.

The results, if they turn out to be those expected today, will permit us to validate magnetic fusion as a process sufficiently mature to envision the next phase of reactor prototyping (often referred to as DEMO) with, in particular the industrialisation and commercially profitable dimensions, which are not part of the missions of ITER.