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Opinion

Nuclear fission: From E. Fermi to Adm. Rickover, to industrial exploitation, to nowadays challenges

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Abstract. Nuclear fission energy reached a multiple bifurcation point: it may continue to decline in some countries, it may expand in other countries, large reactors may extinguish, small and/or micro reactors may exponentially grow in number, sodium fast reactors and innovative reactors may have a bright future or no future at all, thorium fuel might be used or might remain embedded into the terrestrial crust. Then, the purpose for the paper is to orient young generation of scientists. A historical excursus of nuclear era is given starting from the discovery of the nucleus and then moving to Einstein and Fermi, to Rickover and to the industry that led the exploitation of the nuclear fission energy for electricity production. The negative role of the web and the Global World Wide Market (GWWM) in creating cages for the thoughts of scientists is portrayed. The nowadays challenges for nuclear technology are discussed. Selected conclusions are: a) nuclear waste is not a technological problem; b) recently discovered nuclear fuel weakness and reactor complexity constitutes a potential threat for safety; c) regulatory framework needs innovation; d) small and micro reactors shall be deployed if large nuclear units survive; e) a new technological safety barrier appears necessary.

Keywords: Nuclear fission history, challenges for nuclear energy, nuclear fuel weaknesses, NPP cost, NPP complexity.

INTRODUCTION

A longer than one century history characterizes the nuclear era during a fast changing world: it took nearly two millennia for G. Galilei to update the ideas of Archimedes and a few hundred years to A. Einstein to improve the physics picture provided by Galilei and Newton. However, during less than a century all discoveries that made possible the exploitation of the fission chain reaction occurred: possibly, the foundations of the nuclear era are still weak and may collapse due to challenges put by the same civilization that originated and took benefit of nuclear energy. In particular, epochal changes for fission energy technology are expected in next few years. Large reactors may be forced to disappear like dinosaurs and the nuclear fission technology may collapse like the dirigible technology; deep research findings in many areas that sustained the nuclear technology are already buried as many pioneers who performed the research; an avalanche is falling down of incompetence and misunderstandings which are at the origin of cost increases for Nuclear Power Plants, delays in project execution and even cancellations. Un-clarified scientific and technical topics become fertile ground for anti-nuclear scientists who have easy access and listening from policy makers.

Challenges affecting those changes may be stated as (nuclear) waste management, proliferation, public acceptance, severe accidents, or chimeras like ‘Gen IV reactors’. During the last couple of decades, undesired and ‘unexpected’ weaknesses for key elements of nuclear fission technology added up, like the nuclear fuel embrittlement (USNRC, 2018), and the debris in the containment sump following Loss of Coolant Accident

(Lee et al., 2014). This gave origin to additional ‘technological challenges’.

Furthermore, the web cage is born that prevents or limits thinking outside of it. This has moving boundaries whose motion is caused by random combination of inputs not necessarily coming from the right scientists in charge of knowledge: ‘who are those scientists?’, ‘do they still exist?’ etc., are the refrain inside the web cage. This actually bounds all activities of humankind, i.e. not only nuclear technology, and it proves to be more restrictive in the case of science and technology and even more in the case of complex matter (e.g. like nuclear fission). In relation to energy matters, the Global World Wide Market (GWWM) identifies ineluctable strategies: any energy source outside the fossil fuel generation creates un-desired perturbations; the renewable energy sources, primarily, solar and wind, are still in the stage of supporting fossil energy generation and, somewhat un-controlled by the GWWM, have been used to postpone a rational use of nuclear energy. Scientists in the area of nuclear technology may happen to operate inside the double cage of web and GWWM: they eventually have little interest and strength to recognize the ‘real’ challenges or to provide opinions which may collide with strategies of fund managers.

Recently, the 80thanniversary since the Nobel Prize given to E. Fermi was commemorated at University of Pisa, with hundreds undergraduate students attending the event, Interdepartmental Center B. Pontecorvo, 2018. Various speeches dealt with the history of nuclear fission: there was no hold to predict the decline of a technology that was contributed by several Nobel Prize scientists in the XX century, thus triggering the question ‘what is wrong with nuclear fission technology?’

Changes, challenges, cages and commemoration, constitute the motivation and the framework for the present STOP (or, Science and Technology Opinion Paper). All of this is not new: already in 1979 a pioneer of nuclear fission reacted with a paper to the Three Mile Accident (Weinberg, 1979); this was preceded and followed by other papers from the same and other authors (some of those mentioned in the following) always questioning the role, the status and the perspectives of nuclear energy. Nevertheless, the general objective for the present paper was fixed and addresses the question <what can keep the nuclear fission technology alive?>. This has been split into three more viable enquiry statements:

- What stays behind the nuclear technology?
- What is the opinion about the current challenges (for nuclear technology)?
- What went wrong with electricity production by nuclear fission?

A comprehensive answer to those questions is still ambitious and difficult within a paper:

- a tentative answer was already proposed related to Japan early in this century (Tsujikura, 2000);
- a hopeful answer is provided by Gu (2018), mostly focused towards reactor safety;
- a broad vision can be found by Kessides (2012), where the connection between costs and nuclear technology exploitation is discussed into detail.

Hereafter further constraints are introduced to the possible answers and to the objectives of the paper. In the former case (questions), one easily realizes that nuclear technology implies many technologies ranging from mechanics, to civil, to electric, to electronics, to chemical, to soil and so on: we restrict our investigation to nuclear physics, nuclear fission and operational reactors. In the latter case (objectives), a neither comprehensive nor systematic answer is provided (to the bullet questions); inadequate scientific rigor may characterize the discussion. Furthermore, the potential contribution of nuclear energy to environment preservation is not considered: this would require a specific paper (or much more than that); it may be just mentioned that, already in 1989, the connection between nuclear technology and climate changes constituted the motivation for a Journal paper (Till, 1989).

Rather, the expected objective for the present paper is to stimulate the discussion (maybe challenging the web!) around the concerned aspects and, possibly to encourage pursuing the identified strategies (or the author opinions).

TRACKING A SPOT HISTORY OF NUCLEAR FISSION

The commemoration of the Nobel Prize given to E. Fermi, made easy a spot history of fission energy: the overview of the nuclear physics history (Maiani, 2018; Marcucci, 2018), with fission part of it, was simplified into a fewer events till the Fermi Pile and extended afterwards to the exploitation of fission for energy production till nowadays. Not having the skill of nuclear physicists, apologies are given for ignoring significant events.

A collection of key fission related events is given in Figure 1: the nuclear fission story. The Nuclear Era starts when the atom was found not to be ‘indivisible’. The Nuclear Era is subdivided into the ‘The Emergent Nuclear Physics’ followed by the ‘Exploitation of Fission’; these are separated by the landmark of demonstration of operability of the Fermi Pile in 1942.

The Fermi Age is unconventionally fixed to start when E. Fermi commented the Einstein $E=mc^2$ finding in a published paper and to finish at the time of the pile. Later on in the given picture, although Fermi still had a key role in forthcoming science events, ‘The Pioneers (Age)’ took place in a world shaped by the WWII. Noticeably, Admiral Rickover and Soviet Union (URSS) scientists brought the society to the start of ‘The Industry (Age)’ in 1954, the same year when Fermi died.

A bright perspective for nuclear fission opens the Industry Age. The industry was flourishing when United States Atomic Energy Commission (USAEC) issued the Interim Acceptance Criteria for the Emergency Core Cooling Systems (ECCS) (USAEC, 1971). Shortly later Rasmussen published his famous report (USNRC, 1975). The two events together with the availability of powerful computers and huge research investments started new technological branches, i.e. Deterministic Safety Assessment (DSA) and Probabilistic Safety Assessment (PSA), grey arrows on the left of the diagram. These allowed the full demonstration of reactor safety in the subsequent couples of decades.

Unfortunate events happened during the ‘Industry (Age)’ which brought, during a quarter of century, to the decline of fission technology for energy production: the start of the decline is fixed at the time of the Three Mile Island accident in 1979.

The decline could not be arrested till nowadays and other (nuclear) disasters contributed. Currently and starting from Fukushima event (2011), possibly continuing during the decade 2020, nuclear technology lays on the verge of a chasm, or the watershed in Figure 1, at least in the Countries, part of the former Western World, where it was developed.

FROM NUCLEUS DISCOVERY TO THE E. FERMI INTUITION(S)

The history of nuclear physics is much more rich and complex than the spot notes provided below; those notes aim at substantiating the conclusions (more details can be found in the already cited works by Interdepartmental Center B. Pontecorvo (2018), Maiani (2018) and Marcucci (2018). Reference is made hereafter to Figure 1, from 1896 to 1942, distinguishing two periods.

The Discoveries (I)

J.J. Thompson in 1897 measured the fluorescence caused by particles that detach from the (atoms of the) cathode: the atom is not indivisible. Almost in the same year, A.H. Becquerel, M. Curie and P. Curie discover the natural radioactivity of Uranium (Becquerel), Polonium and Radium (Curie). The pioneers of nuclear physics started moving: amazing discoveries took place in the following years (Marcucci, 2018).

In 1911, E. Rutheford realized that “*the greater part of the mass of the atom was concentrated in a minute nucleus*” (Marcucci, 2018). The stability of the atom, the discovery of proton and the quantum mechanics followed. A couple of decades were still needed to arrive at the neutron (see below).

Within a sort of virtual competition with nuclear physicists, in 1905 A. Einstein proposed the Special Relativity (starting from Galileo and Newton and passing through Lorentz and Poincaré) noting that the laws of physics are the same for all non-accelerating observers, and that the speed of light in a vacuum is independent of the motion of all observers. He also proposed new concepts of space and time.

The $E = mc^2$ equation was established.

[The interpretation of reality was not yet adequate for the genius: Einstein engaged himself in a much bigger effort to arrive at the General Relativity in 1915. With the help of complex mathematics and mathematicians (e.g. the already established, i.e. by Riemann, framework for tensor calculus, and the elaborations by Curbastro and his student T. Levi-Civita with whom Einstein exchanged a long lasting correspondence) he determined that gravity, namely associated with massive objects, causes a distortion in space-time and in the propagation line of the light (very rough synthesis: impossible to do better!). The theory implied an incredible number of consequences including the black holes and the gravity waves, which after one century since their proposal are still under experimental investigation by physicists].

The Fermi Age (II)

Without having provided a consistent description of the first period and without mentioning the role of dozens eminent scientists including Nobel Prize recipients, the second period is entered. Exciting researches continued, e.g. including the discovery of deuterium, of neutrinos and of the spectrum of β-decay (E. Fermi had a role in the last two ones); however focus is given to selected fission relevant findings, only.

The start of the Fermi Age period is fixed in 1923, one year after E. Fermi (born 1901) graduation in Physics at ‘Scuola Normale’ in Pisa: in a paper published in a journal he commented the Einstein finding from Special Relativity “ … energy in one gram of matter greater than energy produced by three years of a 1000 HP engine … “. He was well aware (as he directly wrote) at this time of the immense power available to anyone who might trigger the process of converting mass into energy. This happened nearly 20 year before he could demonstrate how that energy can be produced!

During the years 1930, 1931 and 1932 a few scientists (Figure 1), noticeably including the daughter of Pierre and Marie Curie, her husband and Chadwick identified the new particle: the neutron.

In 1934 the group of researchers (‘the boys of Via Panisperna’ in Roma including Rasetti, Majorana, Pontecorvo, Amaldi, D’Agostino and E. Segrè, other than Fermi) were working with a rudimental neutron source, originally constituted by polonium (alfa emitter)-beryllium (target), later on substituted by radon-beryllium, Interdepartmental Center B. Pontecorvo (2018). For

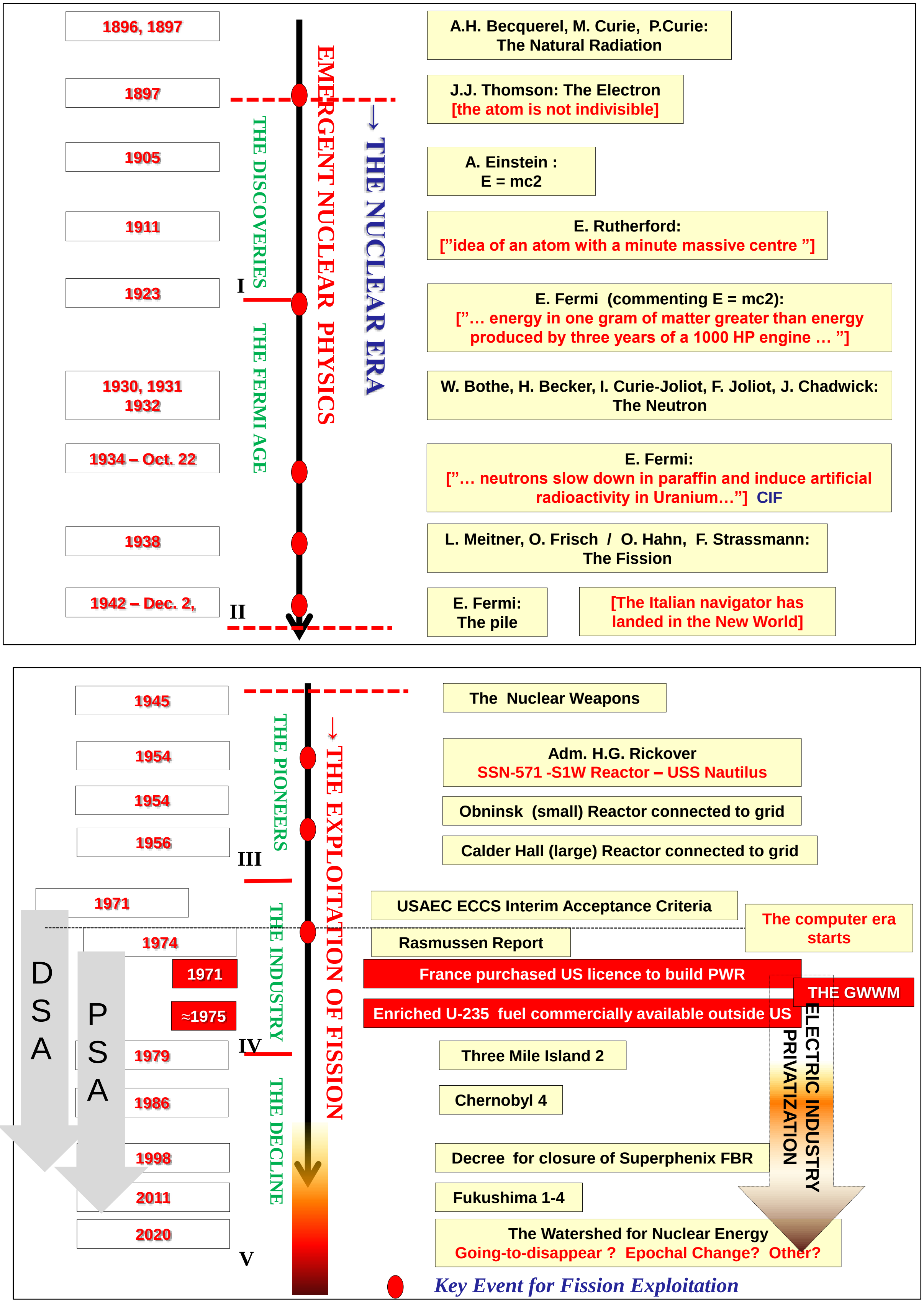

Figure 1. The rough story of nuclear fission.

several months Fermi and his group were measuring artificial radioactivity induced by the neutron source on different target elements including Uranium. They got radioactivity data of difficult interpretation: measured data changed when moving from one room to another (using work tables of different material!). Monday, Oct. 22, 1934, Fermi was alone in the laboratory: he put a block of paraffin between the neutron source and the target; the measured radioactivity increased dramatically. When he was asked why he put paraffin he exclaimed CIF (= “Con Ingegno Fenomenale!”, or “What a big intuition!”). Actually, he declared that new transuranic elements were formed (… *but who knows what he had in mind?*).

In 1938, two couples of scientists (Figure 1) formally discovered the fission. In the same year the group pf researchers of Via Panisperna dissolved and Fermi received the Nobel Prize (in Sweden). Then, he and his wife moved directly from Stockholm to US. The prize was given because of “ *… demonstrations of the existence of new radioactive elements produced by neutron irradiation, and for his related discovery of nuclear reactions brought about by slow neutrons*.” In his speech (Title is “*Artificial radioactivity produced by neutron bombardment*”) he confirmed the hypothesis of transuranic elements, although in a footnote he noted “*… the discovery by Hahn and Strassmann of barium among the disintegration products … makes it necessary to reexamine <whether it> … might be found to be product of splitting of uranium*.”

Since 1939 Fermi worked in US at Columbia University in New York together with Zinn, Szilard and Anderson; the Manhattan Project started. After Pearl Harbor (1941, Dec. 7th) Fermi left New York, and after a few months commuting he moved to Chicago at the Metallurgical Laboratory, which had been established to continue the Manhattan Project.

In 1942, Dec. 2nd, 03:25 pm, local time, the first controlled nuclear chain reaction under Chicago's athletic stadium was demonstrated, i.e. the landmark: the Pile was started up, brought to criticality, showing self-sustaining of the fission reaction, then shut down in approximately half an hour before thermal power and radioactivity became too high. The Pile was conceived to open the way to novel reactors producing plutonium.

Subsequently, during World War II, Fermi became one of the leaders of the Manhattan Project; later on, together with Einstein, he expressed concerns about the development of the fusion bomb. Fermi died Nov. 28, 1954.

SHAPING THE ROW DISCOVERIES OF NUCLEAR SCIENCE (III)

The demonstration of sustainability of the fission reaction (section 3) is a fundamental landmark for mankind equivalent to the discovery of fire, achieving the ability to produce carbon steel products (the “Iron Age”), the discovery of thermal engine, or the proposition of the “E = mc2” formula. The war period (WWII) plus the situation that groups of scientists in opponent Countries were working to pursue the same objective (i.e. a powerful bomb), overshadowed the importance of the Fermi Pile.

The nuclear weapon explosions in 1945 did not contribute to valorize the strategic role of the Fermi Pile. Rather, the weapon argument continues nowadays to obscure the significance of that discovery.

At that historical moment, i.e. the end of the WWII, Admiral Rickover entered the nuclear era. ‘Adm.’ (part of the title of the paper) can be interpreted as ‘admired’ or ‘admirable’. Admiral H. G. Rickover was like a sculptor who modeled the row science material and contributed to create a wonderful statue or the power producing PWR: the first nuclear-powered engine and the first atomic-powered submarine, the USS Nautilus, were launched in 1954 (Figure 1).

As in the case of Fermi, several books have been written to describe the life and the findings of Rickover. Here we only try to depict the essential characters of his creation, i.e. what we call the Admiral Rickover PWR (AR-PWR).

In the AR-PWR, the core constituted by cylindrical fuel rods was conceived and the water was chosen as working fluid, e.g. acting simultaneously as coolant for the nuclear fuel and moderator for the fission neutrons. The water was selected considering half-dozen different fluids as coolants (or even solids as moderators): this brought to the difficult-to-manage constraint of low thermal efficiency, with the (big) advantage of knowing the physical properties and the chemical interactions with other materials in the core.

The selection of water fixed a roadmap involving the high pressure and the consideration of the vessel as the key component for the system design. Other peculiarities of the resulting PWR loop can be stated as follows:

1) Avoid saturated boiling in the core to preserve the uniformity of neutron flux as much as possible.
2) Introduce steam generators to allow boiling and steam production, i.e. in a fluid different from the fluid passing through the core, suitable to move a turbine.
3) Mutual elevation in a gravity environment between core and steam generators in such a way that natural circulation can remove the decay power should main coolant pumps go out of order.
4) Piping connection with the pressure vessel at an elevation above the core and with a size (pipe diameter small enough) to allow core cooling following the unfortunate event of pipe break.

The design of PWR incidentally included technological facets which made difficult its replicas; key ones are the pressure vessel itself with thick walls unsuited even for heavy industry, the sophisticate control rod drive mechanisms including related precision requirements and the need for fuel enrichment.

The connection of nuclear reactor driven turbo-alternators to the electrical grid in 1954 and 1956 (Figure 1) or the early demonstration, (Dec. 20, 1951) by the Experimental Breeder Reactor in Idaho (US DOE, 1994), of electricity generation to light four 200-watt bulbs symbolize the beginning of the nuclear power industry.

THE INDUSTRIAL DEPLOYMENT

Basically, the nuclear industry was “ready to go” when the submarine completed its testing: Adm. Rickover successfully and timely completed an incredible mission!

Summary overview – periods IV and V in Figure 1

Pioneering industries (not a comprehensive list) including PWR and Boiling Water Reactors (BWR) technologies, were:

1) Westinghouse and B&W in US for PWR, since early 50’s.
2) GE in US for BWR, since late 50’s.
3) ASEA in Sweden for both PWR and BWR since early 60’s.
4) KWU in Germany for both PWR and BWR since early 60’s.
5) Soviet Union State Industry for PWR since early 50’s.
6) FRAMATOME in France since 60’s.
7) HITACHI and TOSHIBA in Japan since early 60’s.

In this list only ‘light water reactor technologies’ are considered: heavy water moderated, gas cooled (graphite moderated), Russian boiling water (graphite moderated) and fast reactors were also designed in the 50’s and early entered into commercial operation (Figure 1). Reactors focusing to plutonium production are also excluded from the list: other than devoted plants, non-vessel type reactors simultaneously produced electricity and plutonium in some Countries. Industries in China and Korea took benefit of the early developments and lately entered into the light water (vessel type) nuclear technology market; the cases of India and Pakistan are similar, however, national industries in those Countries did not [yet] enter the international market. Since about the end of 60’s (and till nowadays) more than 90% of nuclear electricity produced worldwide was originated by listed reactors or reactor types.

About 500 reactors have been built and generated electricity since 1960. About 100 reactors have been decommissioned and no more than 450 reactors were producing electricity at the same moment, so far. During the period 1960-2020, about 2×10^4 reactor-years and 10^5 TW-hr are expected to cumulate and to be generated by nuclear fission, respectively. This is equivalent to about 10% the total electricity production and corresponds to less than 5% the world total energy consumption (period 1960-2020).

It is well beyond the purpose of the present paper to evaluate those values or the competing energy sources. The only one qualitative comment is: the number of nuclear fission reactors constructed since 1960 and the total amount of electrical energy generated are far less than expected and far less than what would have been technologically feasible.

Focus on period IV – Figure 1

The existence of nuclear reactors implied huge research investments which contributed to technological growth of the Countries where the reactors were constructed or planned: this is specifically true for the former “Western World” including North-America, West Europe and Japan.

Until 1979 safety records for civil nuclear power plants were excellent everywhere, i.e. no sign of safety weaknesses (more details in the next paragraph); costs and construction time were under control; no public opposition was detectable: the importance of Fast Breeder Reactors to close the fuel cycle was recognized and related projects were in due course; the future for fission energy was bright.

A refrain from nuclear teachers at University till before the TMI-2 accident (1979), was that nuclear technology as a difference from any other technology (oil, chemistry, car, etc.) has never induced fatalities with the noticeable exception of the SL-1 research reactor in Idaho (CE, 1961) (this ‘refrain’ was actually questionable, because, in addition to SL-1 other nuclear technology induced fatalities occurred in the period 1955-1979 – not further discussed here).

The Rasmussen report, 1974, i.e. a landmark in nuclear technology (Figure 1), see the historical development of Probabilistic Risk assessment by Keller and Modarres (2005), shed new light in reactor safety showing that several elements of the reactor design and operation needed substantial improvements. On the other hand, the same report also demonstrated that current safety standards of nuclear technology were higher (or much better) than in other sectors of human civilization like transportation and car industry, health care, etc.; however, the comparison of fatalities and injuries coming from heterogeneous sectors of civilization might not prove to be fully justified.

The United States of America maintained, since 1960, a leading role in the commercialization and spreading of nuclear technology in the world, i.e. by selling nuclear reactors and unavoidably related technology to several countries including ‘Western’ EU, Japan, India, Taiwan, Brazil, Mexico, and even Yugoslavia: in the last Country this was a ‘political’ achievement during the cold war.

We first note that the Fossil Oil & Gas (FOG) is a key element of the GWWM and, at the economic level, ‘Fossil’ is an evident competitor of ‘Fissile’ for electricity generation. The red marked events and the arrow (right side in Figure 1) of the FOG driven GWWM, starting during the 1970 decade, include:

a) The formal buying of patents to construct nuclear reactors e.g. by France and other European Countries and Japan (only France mentioned in Figure 1).
b) The acquisition of the ability to produce and sell of enriched uranium (U-235) outside the US: U-235 was already produced in industrial quantities in the former Soviet Union, however possibilities to sell nuclear fuel to the Western World were severely limited or non-existent during the cold war time.
c) The privatization of electricity industry (Houston, 1991), right arrow in Figure 1: although the privatization idea was born in the late 50’s to improve the industry performance inside a competitive market (Vlahinic, 2011), it received an impulse for the electric sector in the USA towards the end of 70’s and later on reflected in EU; noticeably, France was among the last Countries to adapt the electricity industry to the new market exigence.

The consequence of the first two items upon the nuclear industry can be easily perceived, i.e. lower interest from the USA to expand the nuclear energy market; otherwise a more subtle impact comes from privatization. Privatization, together with the unavoidable split of ownership of energy market quotas, makes difficult large investments and long term (several decades) strategies, which are intrinsic characteristics or needs for the nuclear industry.

The given picture introduces the nuclear accidents (next section) which, among the other things, were postulated by the Rasmussen report.

THE NUCLEAR ACCIDENTS AND THE DECLINE (V)

Nuclear accidents strongly affected the nuclear era (so far). The description of major accidents is well beyond the purposes of the paper: details of the technological conditions that brought to the accidents as well as the concerned system performances before the loss of core geometric integrity core is given by Galassi and D’Auria (2017). Here a few notes are outlined.

The Three Mile Island (TMI-2) accident occurred in 1979 which had, at least, one less severe precursor in another US reactor. Human errors on the site (operator mistakes) associated with some inadequate knowledge transfer between research findings and industrial applications had a role for causing the core melt. However, safety barriers constituted by pressure boundary for primary fluid and containment proved to be strong enough and negligible radiation impact upon environment occurred. Noticeably, the TMI-2 type of event is part of the findings of the Rasmussen report.

The Chernobyl (Chernobyl-4) accident occurred in 1986 within the Soviet Union (USSR) boundaries. A large impact of radioactivity on the site and all over the world followed; fatalities happened. Humans (not only operators on the site) drove the accident or the reactor status till the moment when the explosion occurred. Notwithstanding different consideration of safety in USSR compared with the Western World, the Chernobyl-4 explosion should be seen as a bus or a plane crash deliberately caused by the driver or the pilot: no technological countermeasure could have been sufficient to prevent the disaster. The Chernobyl-4 event (i.e. humans driven) should be considered out of the Rasmussen framework of investigation. Recent investigation (De Geer et al., 2018), sheds new light upon the evolution of the accident scenario, i.e. bringing proofs of a precursor burst in a small core region, which however cannot yet be justified without introducing a deliberate human act.

In 2011 the Fukushima-Daiichi tsunami-caused event occurred involving the units 1-4. This might be considered as the only ‘genuine’ (in the sense of not significantly affected by human role) nuclear catastrophe: a natural event with a predictable severity was the origin of the disaster. The impact of operators in making worse the accident evolution was negligible or non-existent, although an undue and unexpected (in a moment of high mental stress) outstanding reaction from operators could have reduced the severity of the radioactivity releases. Furthermore, DSA and PSA view-points can be summarized as follows, respectively: 1) a negative human role might be addebted to safety technicians in charge of determining the severity of external hazards based on updated information; related information was available years or decades before event and at that time the human failure possibly occurred; 2) the application of the Rasmussen approach, considering <10^{-4} reactor/year> probability of core melt for the concerned reactors and the <10^{4} reactor-year> accumulated operation time since the last core melt accident (i.e. TMI-2 in 1979), should avoid any astonishment for the occurrence.

Within the former Western World, with a few exceptions, the decline for nuclear fission applications to electricity production started in 1979 with step fallings in 1986 and 2011, as already mentioned. The failures bringing to those accidents are associated with the technology itself and not with humans; this attitude corresponds to blaming car industry following deliberate car driver crash. Otherwise, the lack of (or the weak) connection between accidents and nuclear technology should be derived from the given outlook.

A few additional notes provide hereafter a broader perspective for the nuclear fission technology during the decline period (i.e. the decline occurring within the former Western World):

- Ruling out Fast Breeder Reactor (FBR) projects, one example reported in Figure 1, creates the conditions for collapsing the fission technology (this is true independently from more or less recent proposals dealing with possibilities to exploit the energy stored in fuel exiting the core): on the one hand using only a fraction of enriched uranium (as in current Water Cooled Nuclear Reactors) implies a not-easily-acceptable wasting of energy resources; on the other hand, accumulation of plutonium imposes additional costs and social and political challenges.

- During the last few years (e.g. 2012-2018) about 2500 TW-hr are generated per year by nuclear fission energy world-wide: this contributes to a reduction in CO_2 emissions and to the financial stability of the Countries where it is adopted, i.e. a target for the GWWM.
- Ironically at a time when DSA and PSA allowed the confirmation of the safety-robustness of nuclear reactor design and operation (i.e. starting from the year 2000, Figure 1), based on the execution of majestic research programs, the existence of those reactors became questionable.
- Signals of decline for nuclear technology are relatively imperceptible or non-existent in Russia, China and India. Each of those Countries has a relation with the GWWM not comparable with any other Western Country where nuclear technology is declining. In the cases of India and China, the nuclear option is unavoidable to reduce the pollution in densely populated areas. In the cases of Russia and China, the nuclear option has a strategic and political validity and constitutes a financial opportunity, e.g. when in-home designed nuclear reactors are exported towards foreign Countries.
- A bounce of 'new' Countries are considering to embark into nuclear technology: not any of those Countries has a long term energy strategy (i.e. several decades), political stability and financial resources which make viable the nuclear option; in all cases a support from either selected (former) Western Countries or from one among Russia and China (India to a lower extent, nowadays) is needed.

Motivations for the decline and challenges to be considered for possible restoration of a reasonable role for nuclear fission technology are discussed in subsequently.

HERE WE ARE: THE TODAY CHALLENGES

The web and the GWWM created a cage for thoughts (as mentioned above): the nuclear technology, because of its potential effect upon the market and the associated concept of risk perception which can be easily wrought, is one hostage in the cage.

Intuitions rather than results of rigorous investigations are described hereafter; an attempt is made to reproduce at low level the situation of E. Fermi when he discovered the generation of slow neutrons and wrongly predicted the existence of transuranic elements; his thoughts were assessed by others and the science progressed:

hopefully, in the future, if somebody follows-up with thoughts below, one may state CIF!

All identified challenges should be of concern in order to arrest the decline of the nuclear fission technology. Moreover,

- the 'zero-challenge' is defined as a questionable defiance of the society when dealing with the nuclear technology;
- the 'high-level-challenges' constitute the emblematic drawbacks or issues which are associated with nuclear technology;
- the 'technological challenges' shall be seen as needed improvements to foster the technology.

The 'zero-challenges'

Public information and education are the essential cross-points for any viable change in the perspectives for nuclear fission energy: this is the first 'zero-challenge'. No person may accept to live close to a properly shielded radiation source, but almost everybody lives close to (and/or accepts to walk around) a fossil fuel deposit: one may consider the gas stations, the gas pipelines crossing any city and or the oil transporters. Without entering into obvious differences between radiation and fossil fuel deposits let's just introduce a trivial statement:

- Becquerel unit is used as a measure of radioactivity and any expert may easily pass to Sievert and calculate how many fatalities can be associated with a given amount of radioactivity. That's fine: however given a quantity of fossil fuel (oil or gas, mass or volume), there is no unit change to estimate the number of fatalities to associate with a given amount of fossil substance.

The observation can be extended to other sectors of civilization. So, the first 'zero-challenge' is the need to reformulate the perception of danger and/or of risk.

The second 'zero-challenge' is associated with observing that climate change or, better, whatever affects the pollution in the atmosphere, can be mitigated by the exploitation of nuclear fission energy. The today perspectives for electric cars (i.e. increased demand for electricity) may foster the need for nuclear fission energy in a 'clean' world (see also the paper by Till (1989), already cited).

The third 'zero-challenge' comes from observing that in an earth occupied by ground and ocean where animals and humans shall coexist as well as plantations, forests and deserts, the space minimization for any civilization need, the energy in the present case, shall constitute a target to be pursued. Fission energy is by far the most efficient way to produce power per unit land, see e.g. D'Auria (2001).

The fourth 'zero-challenge' is connected with the cost of a nuclear reactor. The issue here is that the cost of a single NPP unit equipped with a large reactor can be as high as 10 Billion USD. This is well above any industrial product or system in other sectors of society; however, large society development investments including improvements of quality standards have been made possible because of nuclear technology. The huge cost, either per reactor-unit or per unit-generated-energy, shall be seen as a fictitious way to establish the convenience of the nuclear fission technology.

In order to outline this concept, we can imagine a conscious scientist living any time till the XVIII century or nowadays in the desert. He would have never developed any nuclear reactor or any diesel engine and the best solution for getting energy needs would have been <heat-up with solar energy or wood fire and use the horse for transportation>. The same scientist, living during the current technological world, would conclude <nuclear energy is a nature resource to be exploited independent of its cost, consistently with other energy sources>. Furthermore,

a) the cost of nuclear energy (fourth 'zero-challenge'), e.g. the construction cost per unit core power, Lovering et al. (2016), "*accelerated*" or "*skyrocketed*" towards the end of '70's, see also Grubler, (2010), Kessides, (2012) and Cooper (2014). Possibly this happened in connection with the investment needed for the introduction and the development of DSA and PSA technologies (Figure 1): the nuclear energy costs could fall down again once those technologies are established.
b) The economic evaluation by Hall et al. (2014), on the one hand shows a low energy return on investment (EROI) value for nuclear fuel compared with fossil fuels, on the other hand the decrease of EROI for fossil fuels during the years and a possible overall inadequacy of EROI analyses (*… they do not include … important data such as climate change, air quality, health benefits …*) are identified.

Cost is a quality of energy production: however, costs of electricity from a nuclear reactor and from falling water or burning wood may not be comparable: in the case of nuclear power, cost and progress of civilization are tightly connected.

Finally, a 'no-challenge-at-all' (or the fifth 'zero-challenge') for nuclear fission energy is an intrinsic element of the GWWM itself (Figure 1). The energy production has the leading role in sustaining the market: any surplus production of (nuclear electricity) energy has the potential to disrupt or to modify the existing equilibrium that is not the strategy for many countries.

The high level challenges

A wide variety of challenges are used to portrait the nuclear technology. Some of those are considered hereafter and all require deep argumentation which is beyond the purpose of the present document. Rather, opinions are proposed eventually in a provocative way in order to stimulate further discussions.

The nuclear waste: If the target is the achievement of zero (or human tolerable) radioactivity from the residuals of nuclear fuel, the waste issue has no solution: possible proposed solutions like launching in the space or incineration (by accelerator) are technologically undue. However, a) humans co-exist with any type of never decaying chemical poison even much more dangerous than nuclear waste per unit size; b) the volume or the weight of nuclear waste is lower than any civil waste by different orders of magnitude. The vitrification process also as the result of nuclear fuel reprocessing and the consequent further size reduction of nuclear waste is industrially viable; related costs are affordable. Optimization in nuclear waste policies is continuously needed. The nuclear waste issue shall not be seen as a rational obstacle for the use of nuclear fission for electricity production.

The nuclear proliferation: The proliferation already happened in the prehistory in relation to fire, in Middle Age in relation to gunpowder, in the last century e.g. starting from WWI in relation to poisoned gas and more recently in relation to biological agents. Proliferation of nuclear material suitable for weapons shall be avoided or minimized. Under those circumstances, proliferation has little or no connection with the use of nuclear fission for electricity production.

The severe accidents: Severe accidents involving core melt or, worse, radioactivity releases to the environment were not originally conceived within the design of nuclear reactors. Unfortunately those accidents happened, although they were caused directly or indirectly by humans. Nowadays severe accidents are part of the design of reactors; however, not even entering the discussion about the common-cause-failure, at least two philosophical questions, which have no accepted answer, occur: A) What is the minimum probability for a severe accident that needs consideration in the design? B) At any time several high probability events may occur: each occurrence opens to a new spectrum of severe accidents. The question is: To what extent the new spectrum needs to be considered in the design? The opinion that we bring into this topic can be summarized as follows (D'Auria et al., 2017; D'Auria et al., 2018):

- The limit probability to be considered for design against severe accidents shall be connected with the expected frequency of fall of a large meteorite upon the NPP site. Population shall accept that a big meteorite can cause a radiological impact.
- A 'new' safety barrier is technologically feasible which, among the other things, based on the continuous detection

of a large number of safety margins, provides a workable response to (all) the issues above.

The decommissioning: Decommissioning of important monuments like the Pyramids in Egypt, the China Great Wall, the Colosseum in Rome, or the Tour Eiffel in Paris is (rightly) never taken into consideration. However, decommissioning of large industrial installations like a highway, an airport of a dam is also (almost) never taken into consideration. Furthermore, in case of an Eolic park (i.e. other than dam another virtual competitor with nuclear energy for electricity production) installed in pristine natural areas, typically on the ridge of hills, the commissioning (hundreds of acres needed to produce the equivalent energy of one nuclear reactor) causes an irreversible impact on the nature: roads need to be created for the installation and the maintenance of the wind mills. A NPP will never be like a Pyramid (no decommissioning needed) however, an 'open-mind' decommissioning needs to be planned without overloading the cost of nuclear fission electricity with the cost of creating a green field soon after the end of operational life.

The low efficiency in nuclear fission exploitation: Low thermal efficiency and very low use of enriched uranium characterize the current fission power generation. Research efforts with industry cooperation are needed: a) to use the low temperature flows at turbine discharge (e.g. improving biological processes); b) to increase the consumption of available fissile material discharged by existing reactors (e.g. in FBR, in homogeneous salt reactors and in natural uranium reactors, etc.).

The non-water cooled technology, Pu-239 and U-233 use: Non water-cooled reactors (except Gen IV reactors, see below) and production of energy from Pu-239 (U-238 origin, in addition to the energy normally produced in current water cooled reactors and in addition to current use of MOX fuel) and U-233 (Th-232 origin), see e.g. Maiorino et al. (2018) and Akbari et al. (2018), have one common aspect: they impact the GWWM. Conscious policy makers are expected to find the way for the exploitation of non-water cooled reactors and of the Pu-239 and U-233 fissile fuels. A strategic vision for gas reactors is available from Penner et al. (2008).

The incident statistics: One may easily find even in scientific literature statements like the following one, see e.g. Wheatley *et al*. (2016), "*… many nuclear safety related events occur year after year, all over the world, in all types of nuclear plants and in all reactor designs and that there are very serious events that go either entirely unnoticed by the broader public or remain significantly under-evaluated when it comes to their potential risk*." The statement may not reflect the reality or may reflect a part of it: a transparent (accessible to the public), centralized, reliable source of data with due information about the barriers which have (or would have) prevented the progression of the incident is needed.

Small, Modular and Micro Reactors (SMMR): Small trees into the woods may grow-up (in some conditions) only in conjunction with large trees; similarly, SMMR are expected to grow in a technological environment fixed by large reactors. In this connection the following can be easily observed: deployment of SMMR is justified when several thousand SMR and perhaps million Micro-reactors are built; the probability of different core melt-down events becomes high. On the one hand, the eventual absence of large reactors may not justify research investments to optimize the safety, thus increasing frequencies of SMMR failures; on the other hand, the same absence may not bring benefits to society as large as to justify nuclear technology. In other terms, without large reactors the (SMMR) nuclear technology may collapse. In the conclusion of a thorough technical and economic analysis, Cooper (2014) wrote: "*The failure of SMR technology makes it impossible to ignore the huge scale that nuclear power demands to succeed*".

The Gen IV: So-called Gen IV reactors (other terms also used) basically are 'future reactors'. By definition during every historical time researchers must look into the future (this is the reason why the word 'chimera' was introduced in the Introduction of the present paper): the deployment of those reactors presumably will not be accomplished by those scientists who are working to the current design. Owing to the same reason, Gen IV reactors are of little of no interest to the GWWM. Therefore, a sort of diluted nuclear technology has formed around the Gen IV, possibly without the rigor associated to the design and the management of existing large reactors where risks and budgets are enormously bigger. So the opinion here is that Gen IV research is valuable, however, a) researchers should be aware that adopted methods including quality of analyses may not reflect what available for current generation of reactors and, b) research funds (typically of public origin) for Gen IV should not deprive budgets to maintain high design and safety standards for existing reactors.

The fusion: The demonstration of controllable fusion (reaction) to produce energy will be another landmark for humankind similar to the discovery of controllable fission (reaction). Hopefully, deployment of fusion will happen and this has the potential to dramatically affect the GWWM. So far, and in the last half-a-century, tokamak based fusion has been a black-hole for budget and a continuously delayed project: we can imagine Leonardo da Vinci who had also the idea of a train in the XVI century starting to build railways and wheels waiting for the discovery of an engine – he did not. ITER fusion reactors looks like a basket for the ideas of researchers rather than an endeavor of human mind: different ways to produce fusion power apparently may deserve more attention from decision makers.

The current WCNR technological challenges

The high safety standards which characterize current generation reactors shall be noticed in advance. Nevertheless, timely improvements consistent with technology and research advancements appear to have been slowed-down in the current situation. Notes below are restricted to nuclear reactor safety and to applications of thermal-hydraulics and nuclear fuel related research findings.

Fuel weakness

Nuclear fuel weaknesses have been characterized during the last couple of decades. In addition to burst and ballooning expected during large break LOCA scenarios, it was found that oxide formation, spallation, crud formation and hydriding may cause brittle failure of the clad, inducing the Pellet Clad Mechanical and Chemical Interactions (PCMI and PCCI) failure mechanisms, specifically under high burn-up conditions. Furthermore, fuel relocation originated by UO2 pellet induced fragility in case of ballooning adds an obstacle to quench front progression during reflood (LOCA case); following the burst occurrence, the fuel relocation causes an additional chemical aggression from water to the interior of the clad and the releases of long-lived fission products into the primary system and the containment; a review of nuclear fuel failure mechanisms can be found by D'Auria et al. (2019). Waiting for Accident Tolerant Fuel (ATF), which will not necessarily address all the concerns during the forthcoming decade, changes in current regulation and the addition of a safety barrier (sections 7.3.6 and 7.3.7) appear a suitable solution to address the issue.

Debris in containment sump

It is well established that debris are formed and may impact the long term cooling in case of LOCA which is based upon the containment sump recirculation: both of ECCS pump cavitation (i.e. lowering the loop available Net Positive Suction Head, NPSH) and channel blockage (e.g. at core inlet) may occur as a consequence of the presence of debris. Solutions proposed, designed and installed by industry, consist in one or more grid layers at the pumps suction location into the containment sump. It seems that more robust solutions are needed like grids with moving parts or robot systems able to displace the debris during the course of the accident (i.e. not an easily achievable situation under high pressure, high temperature, under water and in a high radiation field).

The complexity of existing NPP

An anecdote introduces the complexity subject and also connects nuclear physics and engineering. Rubbia (a physics Nobel Prize) is quoted to exclaim when he saw the industry final design of his concept of the Accelerator Driven System (ADS): "*I provided a simple idea and you ended-up with a complex system*"! The complexity of a current NPP may be better pictured as a two-step process: 1) passing from the Fermi pile to the AR-PWR implied the move from artisan components assembled in the shop to a complex industry system; 2) the AR-PWR has been continuously upgraded to the current PWR with an exponentially growing complexity in the areas of electronics and automatization. The concern here is the consistency between the complexity and the safety; see e.g. D'Auria et al. (2012). The addition of a new, current technology based safety barrier appears a suitable solution to address the issue.

Passive systems

Since the Chernobyl event, passive systems were considered a possible solution to human mistakes. Actually, different features of current WCNR, like mutual position of core and steam generators, steam generator design (or secondary side cooling) and presence of accumulators among the ECCS, are fixed based on passive systems which make use of gravity forces. Passive systems implying a minimum number of components needing external source of energy to operate are apparently attractive from a reliability view point. The key drawback, not receiving sufficient attention, is connected with the thermal-hydraulic operation: low driving forces may be overrun by low intensity perturbations and instability in passive systems performances may be expected (D'Auria, 2018). Reliability of thermal-hydraulic phenomena in passive systems recently became a 'new' research sector: findings and procedures are available and need to be considered by regulators and designers. Complex (and/or high-tech) active system for core cooling driven by on-site available steam energy, e.g. SPX (2014), might be preferable to more or less 'pure' passive systems like accumulators.

The LBLOCA bifurcation

Large Break LOCA (LBLOCA) constitutes a historic landmark in accident analysis: namely LBLOCA constitutes one key Design Basis Accident (DBA) in safety assessment. As a consequence, the system configuration in the case of WCNR and the ECCS design are based upon LBLOCA which is assumed to occur in the largest pipe connected with the reactor pressure vessel and in the worst position as far as core cooling is concerned. The recently discovered nuclear fuel weaknesses and the potential conflict with current regulation (USNRC, 2018; USAEC, 1971) brings to a bifurcation point where only one of the three statements below is going to be true:

A. LBLOCA is not (anymore) part of the DBA.
B. The WCNR nominal power and/or discharge burnup are (significantly) decreased.
C. The licensing framework is (substantially) modified.

The Leak Before Break (LBB) concept and the quality of construction can be invoked for the option A. The option B. and C. are not tolerable to the industry or to regulators, respectively. The suggestion here is to go in the direction of the option C. Insights into this topic can be found in the paper by Mazzantini et al. (2019).

The regulation

Regulation is a matter for regulators: thoughts for their consideration are provided below. The issues depicted earlier (and papers by D’Auria et al., 2017 and D’Auria et al., 2019) almost unavoidably cause overpassing the safety thresholds defined by the current regulation (USAEC, 1971), or the expected-to-come regulation (USNRC, 2018). Impractical reductions in core power and in tolerable fuel burn-up or unacceptable dropping of LBLOCA from the list of DBA constitute alternatives to the change in regulation (Mazzantini et al., 2019). A three-fold proposal is formulated here:

i) Containment role: containment constitutes an unquestionable robust barrier; radiation releases out-of-containment could be the target of regulations, providing flexibility to radiation releases inside the containment. Design Extension Condition (DEC) could be established with an assigned low probability, hereafter called DECP: the DECP value is lower than the value characterizing the current DBA and higher (however as close as possible) than the expected frequency of the fall of a large meteorite around the concerned reactor site. For accident scenarios having probability less or equal to DECP the containment should constitute the accepted barrier, no matter the radiation release into the containment (D’Auria et al., 2019).
ii) ECC design: keep the current (USAEC, 1971), based, or the modified (USNRC, 2018), ECCS criteria. Namely, keep the currently adopted graded approach (e.g. more restrictive criteria for higher probability events). This implies considering the DECP discussed at item above: current or modified ECCS criteria must be fulfilled for any event having probability higher than DECP; for events having probability smaller than DECP, vessel integrity should be demonstrated and radioactivity releases into containment should be calculated with assigned precision and properly minimized according to ALARA.
iii) New safety barrier: a new safety barrier supported by DSA and PSA should be introduced such to make possible the DECP value.

Another safety barrier

A ‘new technological’ safety barrier which seems unavoidable in view of the identified issues is proposed by D’Auria et al. (2018) and D’Auria et al. (2019). The introduction of the new barrier is expected: a) to deal with the nuclear fuel weakness and the NPP complexity; b) to reduce the core-melt probability down to the value corresponding to the fall of a large meteorite around the concerned NPP site; c) to restore the public confidence towards nuclear technology. The concept for the new barrier is based on the As-Low-As-Reasonably-Achievable (ALARA) principle, the Best Estimate plus Uncertainty (BEPU) approach, the Extended Safety Margin Detection (E-SMD) hardware, the Independent Assessment (IA) requirement and the Emergency Rescue Team (ERT) strategy. A rough estimate for the overall cost for the barrier resulted in the value of 1% the cost of a large size reactor unit.

CONCLUSIONS AND POLICY IMPLICATIONS

Starting with the supposition of the existence of the nucleus, a series of amazing discoveries during half-a-century brought to the demonstration of sustainability of fission reaction: an epochal finding for the humankind. During the following half-a-century, engineers and industries built systems (the NPP) capable of obtaining huge amount of electric power per unit occupied land: an accomplishment out of any imagination possibly for the same physicists who contributed to the early discoveries.

All of this happened during a tiny period for the human civilization and is now endangered, at least in some Countries: the nuclear fission technology is declining and at risk of extinction. Possibly, cages for the thoughts of scientists put by the modern society throughout the web and the GWWM, prevent stopping the decline. Dark years during the Middle-Age are apparently coming back: peoples were living inside their houses [going out was useless (e.g. nothing to buy) or dangerous (risk to be beaten)]: there was no incentive for innovation - current nuclear scientists and technologists may resemble Middle Age peoples.

The present Science and Technology Opinion Paper (STOP) is justified by the depicted frustrating scenario;

let's arrive at conclusions and policy implications, starting from the historical remarks:

- Nuclear physicists during the XX century and Admiral Rickover had no boundaries to their thoughts: their mission was the progress of humankind.
- Nuclear fission history is (too) short, so far, to avoid errors (or the three nuclear disasters).
- Innovative ideas which contribute to the growth of nuclear technology flourished inside a receptive civilization time period (i.e. no cages).
- Errors shall become the springboard for new discoveries.

Namely, the first 'error' (Three Mile Island) was human mistake driven, the second one (Chernobyl) was the results of deliberate human actions and the third one (Fukushima) can be associated as a human failure in safety assessment. Surprisingly no one worries of quality of car or aircraft technology when a bus driver or a pilot deliberately crashes; this is what happened to nuclear technology.

The GWWM is having a key role in slowing down the nuclear industry: key related events, other than the Oil & Gas competition, have been identified as the selling abroad from the US industry of patents for the design and construction of nuclear reactors and the commercial availability in EU of enriched uranium. Furthermore, the privatization of the electric industry made problematic long term, i.e. several decades, energy strategies, as needed for fission technology exploitation. It should be no surprise noting that in Countries, like Russia, China and India, where the national Government have a direct leadership on the energy sector (i.e. outside of the GWWM), the nuclear energy can easily endure. Various challenges have the potential to impact the survival of nuclear technology nowadays; three categories have been identified:

I) The 'zero-challenges' are defiance of the society: nuclear technologists cannot fight alone those challenges which include the fear for radiation, the cost of the technology (i.e. the cost of progress in civilization) and the competition with invasive (they occupy wide territories on the earth and are 'popular' in those territories) energy sources.
II) 'High level challenges' are unique constraints unduly imposed as conditions for survival of the nuclear fission technology: these include decommissioning, the importance of one fatality caused by nuclear technology, the negligible probability of occurrences for severe accidents, the nuclear waste, the proliferation and even the expectation for fusion.
III) 'Technological challenges' which are the real challenges: they receive from decision makers and regulators less attention than other identified challenges and, possibly, lower attention than what needed. Selected related findings are:

- Nuclear fuel weaknesses and increasing system complexity affect the safety of existing reactors.
- LBLOCA shall be kept as key design accident scenario in safety analysis.
- Licensing rules require important changes: the strength of current containment should receive proper consideration.
- The introduction of a new safety barrier appears indispensable.

Challenges are (energy) policy implications: poor reaction to challenges may accelerate the decline of nuclear fission technology; not-addressing the technological challenges will create the conditions for new intolerable nuclear disasters. This is specifically true in relation to a new safety barrier. On the other hand, the climate change, or the global warming together with the electric car industry, will open new opportunities for nuclear fission energy. This is 'the challenge' and the policy implication for young generation of scientists and technologists, provided current policy makers will not overrun the progress of humankind.

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ABBREVIATIONS: ADS, Accelerator Driven System; **ALARA,** As Low As Reasonably Achievable; **AR-PWR,** Admiral Rickover PWR; **ATF,** Accident Tolerant Fuel; **BEPU,** Best Estimate Plus Uncertainty; **BWR,** Boiling Water Reactor; **CIF,** What a big Intuition; **DBA,** Design Basis Accident; **DEC,** Design Extension Condition; **DECP,** DEC Probability; **DSA,** Deterministic Safety Assessment; **ECCS,** Emergency Core Cooling Systems; **EROI,** Energy Return On Investment; **ERT,** Emergency Rescue Team; **E-SMD,** Extended Safety Margin Detection; **FBR,** Fast Breeder Reactor; **FOG,** Fossil Oil & Gas; **GWWM,** Global World Wide Market; **IA,** Independent Assessment; **LBB,** Leak Before Break; **LBLOCA,** Large Break LOCA; **LOCA,** Loss of Coolant Accident; **NPP,** Nuclear Power Plant; **NPSH,** Net Positive Suction Head; **PCCI,** Pellet Clad Chemical Interaction; **PCMI,** Pellet Clad Mechanical Interaction; **PSA,** Probabilistic Safety Assessment; **PWR,** Pressurized Water Reactor; **SMMR,** Small Modular and Micro Reactors; **SMR,** Small Modular Reactor; **STOP,** Science and Technology Opinion Paper; **WCNR,** Water Cooled Nuclear Reactor.

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