Ph313, Spring 2011: guidelines for writing the term paper

There are no rigid rules of writing scientific or technical reports, or articles popularizing science, new technologies, etc. However, there are certain "rules of thumb" that have emerged over time. If you take a copy of any scientific journal, you will see that all articles in it are composed in a similar manner, according to the same "general scheme". They consist of distinctive elements, or "building blocks", that are arranged as follows:

- Paper title, followed by the name of the author (or names, if there are two or more authors), and her/his/their affiliation(s). The title has to give the reader a general idea of what the paper is about.
- Abstract: a single-paragraph summary of the entire paper. It should briefly describe the question posed in the paper, and the conclusions. It should be possible to determine the major points of the paper by reading it. The abstract is very important for the reader, because after reading it she/he usually makes a decision of whether the subject is of interest to her/him, and whether the entire paper is worth reading (although the abstract is located at the beginning of the paper, it is easiest to write it after the paper is completed).
- The body of the paper – and it also has to be "structured", i.e., it should contain the following "blocs":
    - (a) a section titled "Introduction" – it should explain why the topic presented in the paper is important. And it may also outline the "general plan" of presenting the material in the main part – for instance, it may identify and briefly describe the "subtopics" that will be discussed in it.
    - (b) The "main section" of the body. It may be a single section, but if the general topic presented in the paper may be split into several "subtopics", it makes sense to divide the "main section" into "subsections", each one discussing a separate "subtopic".
    - (c) A closing section, called "Summary and conclusions" (or "Discussion", or "Closing remarks" – whatever suits the author better). Here the major points of the paper should be again summarized, with a brief discussion (if needed) following, and then a paragraph or two containing the final conclusions. A person writing a report or article usually wants to pass certain message to the reader – so, the closing section is the right place to do that. Of course, the message should be passed to the reader in an elegant manner, using highly logical arguments, not "brutal propaganda".
- Additional sections, such as the list of references quoted in a paper (references are very important, what is written in a good paper always has to be based on trustworthy sources, and the reader must be given a chance to access those sources her/himself. Also, if the paper is not in a final printed form, but in a **manuscript** form, then putting figures and their captions in the main body may not be easy. A common practice is therefore to put the figures – each on a separate page – after the list of references, and to group all captions on yet another page.

As I say, this is not a “rigid recipe”, but time has proven that following the above “rules of thumb” helps to attain maximum clarity of the presented material, and is also a form convenient to a potential reader. In most cases, the reader “scans” the paper not exectly “page by page”, but in the following order: title → abstract → introduction → closing section → and only then the main section. So, the closing section is very often read **before** the main section. It should be kept in mind, and the closing section should give a reader an additional temptation to read the main section, in the case she/he has skipped reading it.

So, I would like you to follow the above “rules of thumb”. Now, some practical instructions, what I expect:

- The title and abstract should be at the first page; the main body should start at Page 2. A reasonable length of the main body, if the paper is written by a *single author,* is five double-spaced pages; and eight pages if there are *two authors.*
- For creating your paper, you will use information extracted from several sources. It should be indicated in the text that the information you present in a given sentence or paragraph has been obtained form an “external source”. The conventional recipe for doing that is very simple – you use “number tags”, either in the form of superscripts (e.g. …*as was shown by J. Smith*[1]*, and was later confirmed by an MIT team*[2]*….*), or numbers in square brackets (e.g., *as was shown by J. Smith [1], and was later confirmed by an MIT team [2]…*), whatever you prefer. At the end of the paper you put a “List of References”, precisely identifying the source, e.g.:

  1. J. Smith, Journal of Applied Physics, vol. **180,** pp. 301-327 (2006).
  2. W. Brown *et al.,* Web document, http://mit.edu/teamwork3217/ (2010).

  There are certain customary rules how to compose such a list – e.g., the volume number of the journal should be in bold face, and if the list of authors is long, you may give only the first name and add “*et al.*”, which is from Latin and means “and co-workers”. The list is essential, because it provides the information necessary for a reader to locate and retrieve any source you cite in the body of the paper. Each source you cite in the paper must appear in your reference list; likewise, each entry in the reference list must be cited in your text.
- There is an old Chinese proverb: *One picture may say more than a thousand words.* This is very true! Therefore, I strongly encourage you to use figures in your paper. It is not necessary to insert them into the text. It will be OK if you write, e.g.: *….as illustrated by Fig. 1, ….* and then place the figure on a separate page at the end of paper, only labeling it as “Figure 1”. It is not even necessary to put the caption on the same page, you may group them all on yet another page titled “Figure Captions”.

OK, this is, more or less, all that comes to my mind right now. If you need more “guidelines”, please don’t hesitate and ask, in class, or come to see me in my office.

An example:

I think it may be a good idea of showing you an “example paper” written in accordance with the guidelines outlined above. Two years ago, when I taught the same course, I started writing a paper about the 1986 Chernobyl disaster, with the intention of using it as an auxiliary material in the course. But I never finished writing it, about 50% of the “main body” is still missing. However, the abstract and the introduction are “ready to go”. So, I think that reading this material, even in its present unfinished stage, may give you some extra “clue” of what my expectations concerning your papers are.

One comment – the Chernobyl paper, if I ever manage to finish it, will be certainly much longer than the “five pages” I mentioned above. So, please treat the paper only as an example illustrating the “general rules of thumb” I have outline above, but please don’t think that I expect to get something of comparable length from you!

You will see that my plan was to compose a text according to the general scheme:
Title – Abstract – Introduction – Main Body – Conclusions. I planned to split the Main Body into three sections, and those sections into subsections. But you should not do that. Sections and subsections are good, but in papers much longer than five pages.

The Chernobyl disaster

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Abstract: The explosion of the Chernobyl reactor in April 1986 was the worst accident in the entire history of nuclear power industry. The two major factors that contributed to that disaster were the design of the reactor which made it "intrinsically unsafe", and a series of human errors. In this paper, we explain why the so-called "positive void coefficient" makes the Chernobyl-type reactors unstable and difficult to control. Also, we explain the mechanism of the "Xenon poisoning", and effect that played a major role in the disaster. Details of the ill-fated experiment that triggered the explosion, and of the irresponsible actions of the operators in the last minutes preceding the explosion are also discussed.

I. INTRODUCTION

The April 1986 explosion of the RBMK-1000 reactor in the Chernobyl Nuclear Power Plant in Soviet Union (today, the accident site is on the territory of the Republic of Ukraine) was the largest catastrophic event in the entire history of the civilian nuclear industry. It had a strong negative impact on the public perception of using nuclear power for generating electricity. Today, when the nuclear sector is regaining public favor as a "zero CO_2 emission" provider of electric power, it is important to identify all factors that contributed to the disaster – those factors included a generally crude technology, faults in the reactor design, as well as ordinary human errors. Needless to say, good understanding of all those factors is a matter of considerable importance – it will help us to avoid such errors in the future, and to build new generations of absolutely fail-safe power reactors.

In this paper, we present a brief overview of the construction details of the RBMK-1000 reactor, with particular emphasis on those that make this water-cooled graphite reactor unstable when running at low power. We explain the mechanism of the "Xenon poisoning" -- in the opinion of experts, this effect played a critical role in the Chernobyl drama. Next, we describe what happened during the hours and the last few minutes preceding the explosion. Finally, present a brief overview of the consequences of the disaster – however, the Chernobyl catastrophe had a pronounced impact on so many areas of life that even a brief summary of *major* consequences would require a much more extensive paper than the present one. Therefore, we do not discuss those issues in detail, but we only give a list of references to articles in which the consequences of Chernobyl disaster are thoroughly reviewed and analyzed.

II. THE REASONS OF THE CHERNOBYL ACCIDENT

I..1. The role of the neutron moderator

In a fission reaction a nucleus of a fissile[1] element (^{235}U or ^{239}Pt) absorbs a neutron, and then breaks up into two "daughter" nuclei, releasing two or three free neutrons. These neutrons can trigger more fission acts, and so a chain reaction develops. However, the neutrons released in the fission process are *fast* neutrons, with energy of the order of 1 MeV. Such neutrons are weakly absorbed by the fissile nuclei; the ones that are readily absorbed are *slow* neutrons, with energies of 1 eV or even lower. Therefore, the fast neutrons have to be slowed down. Neutrons loose kinetic energy if they collide with atomic nuclei – the lighter the nuclei are, the more energy they loose in each collision act. Therefore, in reactors the fuel rods are surrounded by materials with a high content of light atoms. Such material is called the *moderator*.
Hydrogen, which has the lightest nucleus of all elements -- just a single proton -- is a very good "neutron slower". Why? It can be clearly understood if we recall the experiments with elastic collision of hard spheres. Suppose that there are two spheres

[1] In nuclear engineering, a **fissile** material is one that is capable of sustaining a chain reaction of nuclear fission.

with equal masses: sphere A is at rest, and sphere B approaches with speed *V* ; after the collision, sphere B has zero speed, and sphere A flies away with speed *V*. In other words, the two spheres “exchange” their kinetic energies.

However, if the mass of sphere A is much larger that that of sphere B, then sphere B just “bounces back” – its kinetic energy is only slightly lower than before the collision. The remaining portion is acquired by sphere A, but it is such a small portion that sphere A hardly even moves.

Therefore, the lighter is the nucleus, the better neutron moderator it is. Hydrogen has the lightest of all nuclei, and there is plenty of hydrogen in ordinary water. So, water is widely used as a reactor moderator. It’s only disadvantage is that when the neutrons are slowed down to very low speeds, the collisions may no longer be elastic – some neutrons “stick:” to the protons. In other words, in the moderation process some neutrons get *absorbed* by the water moderator.

A better moderator is the so-called heavy water (D_2O) , in which ordinary hydrogen is replaced by its heavier isotope, Deuterium. The mass of Deuterium nucleus, called deuteron, is twice the mass of a single proton – so more collisions are needed for the neutron to get slowed down. However, neutrons very seldom are captured by deuterons – the absorption in heavy water is negligibly small, making D_2O a more efficient moderator than ordinary water. The only disadvantage of D_2O is that it is prohibitively expensive – therefore, it is seldom used in power reactors (the Canadian reactor CANDU is one exception).

Carbon nuclei are even 12 times more massive than hydrogen nuclei – on the other hand, the neutron absorption coefficient of carbon is nearly zero, Graphite, which is a form of carbon, is inexpensive. Therefore, graphite is a good reactor moderator – the very first nuclear reactors ever built were graphite reactors.

Water, in spite of its absorption coefficient, has one considerable advantage – it can be also used as a coolant, i.e., the medium transferring heat out of the reactor. Graphite is a solid, so extra cooling system has to be used – with either water or gas circulating in a system of tubes acting as a coolant. So, the design of a graphite reactor is more complicated – and, as we will see later, there are some safety problems with such reactors. In conclusion, both reactor types have their advantages and drawbacks. It is difficult to say which type is “better” – the choice of the moderator clearly depends on the goals that one wants to achieve.

II.2. The RBMK-1000 reactor and its dual purpose

All power reactors in the US are strictly civilian installations, and they all use water as the moderator and the coolant – either through the “boiling water reactor” (BWR) design, or “pressurized water reactor” (PWR) design.

The Chernobyl reactor was intended to serve dual purpose: one was generating electric power for the civilian sector, and the other was production of plutonium for the Soviet nuclear weapon program. Plutonium is produced in all reactor types: some neutrons are captured by the "inert" component of the nuclear fuel, ^{238}U (natural uranium contains only about 0.7% of the fissile isotope, ^{235}U -- the remaining 99.3% is ^{238}U ; reactor fuel is usually enriched to contain 3-5% of ^{235}U). However, the ^{239}Pt nucleus created by the neutron capture soon itself captures another neutron and changes into ^{240}Pt, which is no longer good for making atomic bombs. Therefore, when the goal is to obtain the ^{239}Pt isotope, the fuel rods have to be removed from the reactor after a short time, 2 or 3 weeks – otherwise, too much of the "product" will be contaminated with the "bad" ^{240}Pt stuff. This is hardly possible in the case of water-cooled reactors, because they are sealed vessels. The fuel is loaded and the reactor works for about 3 years on a single load – then the reactor is shut down and the entire load is replaced by a new one in an operation that typically takes about a month. In the spent fuel rods there is much plutonium, but almost all of it is the "bad" ^{240}Pt isotope.

A plutonium-producing reactor should therefore operate in short cycles 2-3 weeks long, but then it is rather useless as a power source. An alternative is to build a reactor in which fuel rods can be removed without stopping its operation. And only graphite reactors make it possible, because the fuel rods are hot housed in a pressurized sealed vessel, but they just reside in huge block of graphite in vertical tubes that need not to be sealed.

The cooling water in the Chernobyl reactor circulated in a system of additional tubes called "canals" – from that came the name of the reactor type: RBMK in Russian is the acronym of "Reactor Bolshoy Moshnosti Kanalnyi", meaning "High-Power Canal Reactor". The 1000 in the name is the electric power generated in MegaWatts – the thermal power was, of course, much higher, about 3,500 MW.

The Chernobyl reactor was a huge object, about 20 m tall (about the same height as Weniger Hall). A special crane was mounted at the top of the reactor in order to extract the long fuel rods. Altogether, the height of the reactor plus the crane was nearly 40 meters. Common sense dictates that a power reactor and all its paraphernalia should be place inside a sturdy steel-reinforced concrete shell, called a "containment structure"; all US power reactors are housed in such structures. In the case of a leak of radioactive materials they stay inside the containment shell. However, because of the size of the Chernobyl reactor with a crane atop the cost of such structure would be enormous. Therefore, instead of sturdy shell, a lightweight hangar was chosen.

II.3. The "positive void coefficient" of graphite reactors

Power reactors require intensive cooling by water circulating in a network of tubes – therefore, in a graphite reactor there is much water. It not only cools the graphite block, but also acts as an additional moderator and neutron absorber. The "extra" moderation by water is a "good" effect – however, the absorption may be a potential source of troubles. Paradoxically – if it disappears! But how can it disappear? Well, the mechanism here is quite simple. At high temperatures, the water may start boiling, so that bubbles of steam form in the cooling tubes. Such bubbles are called “voids”. Steam has a density much lower than liquid water, and therefore it is a much weaker neutron absorber. Consequently, if voids start forming, neutron flux in the reactor increases, thus intensifying the chain reaction. More heat is generated, further increasing the temperature – the water starts boiling more rapidly, more voids are formed, and the neutron flux increases even more, again intensifying the chain reaction, and so on. In other words, the voids give rise to a *positive feedback* – a very dangerous condition because eventually all water changes into steam and the entire cooling system is knocked out, which invariably leads to the core meltdown.

II.4. The Xenon poisoning effect

II.5. The ill-fated experiment – what was it needed for?

III. CHRONICLE OF THE EVENTS ON THE CRITICAL NIGHT

IV. CONSEQUENCES – THE “CHERNOBYL HERITAGE”

V. SUMMARRY AND CONCLUSION

References

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