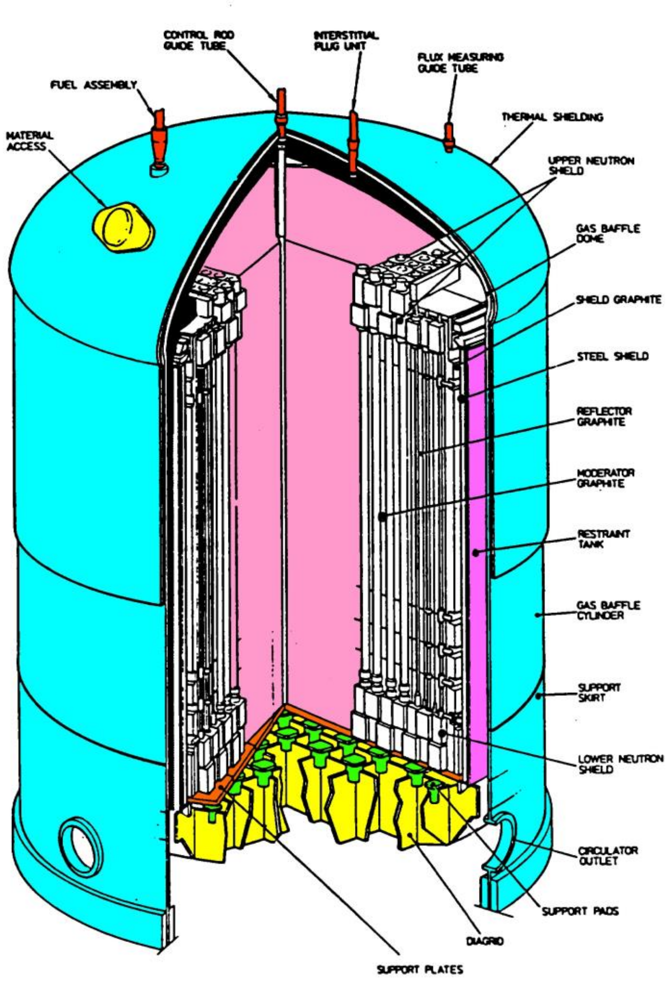
Science Project for year 10

Debris Removal Using Remote Manipulators

The inside of the nuclear reactor is a complicated and crowded place. Furthermore, there is a lot of heat and radioactivity even when the reactor is shut down. Very occasionally things break and parts become loose and fall from where they should be. Sometimes during maintenance work parts are dropped into pipes or openings. Getting them out again is very important. When the reactor is operating, very powerful flows of cooling fluid can sweep debris along – even heavy objects like bolts. Metal plates are even worse: they give more surface area for the pressure of the flow to work on, and if they land in the wrong place they can block coolant flow and prevent heat being taken away. If nuclear fuel pins are not cooled they quickly get too hot and the metal can containing the uranium dioxide fuel may fail releasing fission products into the reactor circuit, which is very undesirable.



The diagram to the left shows part of an Advanced Gas Cooled Reactor (inside the concrete radiation-shielding and pressure vessel). The holes in the blue "gas baffle" are just about big enough for a man to wriggle in – though you would not want to! However, you might sometimes want to put a manipulator or robot through these holes to inspect the reactor (even if there is no debris). For more idea of scale see the picture on the next page which was taken during construction.

Your job is to design a method of recovering debris from a hostile environment. The object to be recovered may be a small bolt or a small plate. It will be located inside an inconveniently narrow space, where there is no direct line of sight from your working position.

You will need to work out how you will locate the item of debris, and then how to grab it and get it out (without getting stuck or dropping it again).

- Which will be easier to pick up and get out, a cylindrical bolt, a plate lying on a flat surface, or a very irregularly shaped machine part?

Methods that have been used in the past include:

- Long, articulated manipulator arms (i.e. they can bend round corners) with grabs attached to the end. They may have a camera attached to the end of the arm.
- Remotely operated small robots with cameras and robot arms.
- Arms with magnets on the end. (However, not everything is magnetic including lots of bits that go into reactors. Test it!)

This shows the top of the "gas baffle" surrounding the reactor core. It is inside the radiation shield. The holes across the top are where we load the fuel assemblies into the reactor. We sometimes use these to send cameras down to inspect the core. However, the place where the man is now standing will be full of pipes when the reactor is finished.

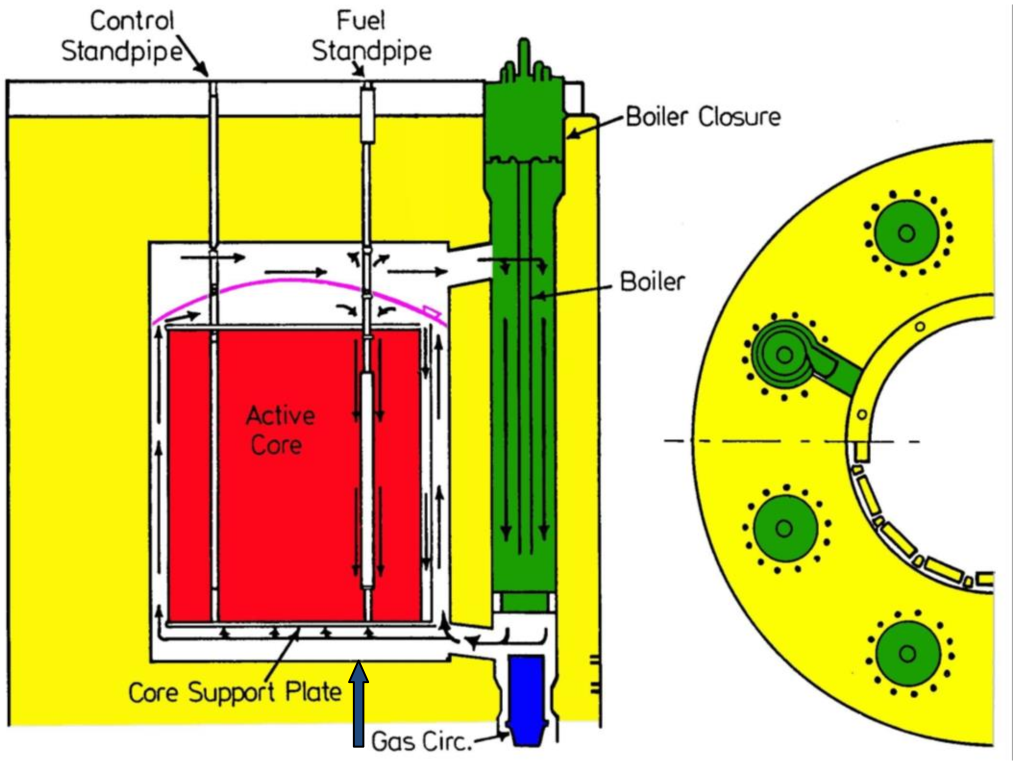
Most large engineering structures are full of awkward corners and inconvenient and hostile spaces, so remote inspection and debris recovery is very important indeed.

This is not one of EDF's designs – but it shows an articulated manipulator. How easy is it to control something on the end of a long arm? How much weight could you carry like that?

Request for Design Proposals

An Advanced Gas Cooled Reactor is in a long maintenance outage. An item of debris has been identified that must be removed before the reactor can restart. The cost of not returning the reactor to service on plan is extremely high (about £1 million per day) so we are inviting a number of teams to independently submit design ideas for a method of removing the debris item in the remaining period of the outage.

Two proposals will be selected for further development. One selection will be based on the criteria that it will have the best chance of being ready to successfully remove *this* particular object out of *this* location in the time available using a combination of well established techniques. It does not have to be adaptable to similar problems elsewhere. We will also select the proposal that offers the possibility of becoming a long-term flexible solution for debris removal.



The designs must have a realistic chance of begin successfully constructed: you are not writing science fiction. You are not, for example, allowed to assume that we can find materials stronger than any currently known or batteries capable of storing more energy than those now available. Most successful inventions tend to be based on an imaginative combination of currently available technologies (for example, the iPad) because you can put things together that meet a need *now*. Hence, we are going to assume that you represent organisations that have had previous experience with *remote operations* – but do not have just the tool to do this job. You can therefore, if you wish, propose adaptations of existing tools that can quickly be modified to do this specific job – but possibly only this job. You can also propose more original techniques that might very adaptable to a range of similar problems. In the real world we would probably ask two teams to build a prototype and test them in competition to see which is best. We might well include in the competition one proposal that is almost certainly able to do the job – but only this job and maybe not as quickly as we would really like, and also one proposal that has more novel elements but with better prospects for doing everything we would like in similar situations in the longer term.

The Problem Scope

We believe that a metal item has fallen into the space underneath the "active" reactor core – which is indicated in red on the diagram above. (We do not know how it got there or what it is. It might have been detached from the reactor internals and been blown there. It might have been dropped down a fuel channel from the refuelling machine, and rattled through the gaps at the bottom. It might have been dropped during maintenance) Very fuzzy and indistinct pictures from a not very well placed remote inspection camera do not give us much information about the debris – we just know that it is there. We have marked the approximate position with a blue arrow.

- It is possibly (but not certainly) stainless steel - perhaps a bolt, a small plate or a spring. That is a guess, based on thinking about what could have come free.
- It might weigh up to 500gm and the longest dimension may be 10cm. That advice is based on the worst case scenario from the fuzzy TV pictures.

Fortunately, the plant is in a long maintenance outage of two months, and late in the outage we are planning to remove the *gas circulator* nearest the dropped item for maintenance. (See the figure above, which gives a side and top bottom view.) The circulator is a pump marked in blue that can be lowered down out of the concrete pressure vessel, leaving a cylindrical hole about 1m diameter. This space has an outlet 50cm in diameter, with a 15° upward slope, into the under-reactor space. This space is about 1m high. The debris item is about 4m from the pressure vessel wall. (The reactor "active" core is a10m in diameter, to give you a sense of scale. However, the size of the access holes has been slightly exaggerated for clarity in the figure.) You will have a clear space 3m high underneath the circulator hole to mount equipment outside the reactor.

The reactor will be shut down and cool (but only relatively – it is still at 50 deg C). The under-reactor space is too radioactive for human life, but not enough to damage electronics.

Problem Constraints

Foreign Material Exclusion

All solid metals are made of closely interlocking small crystals (known as "grains"). Their strength comes from the way the grains stick together. Unfortunately, when the stainless steel inside AGRs comes into contact with anything containing fluorine or chlorine, atoms of these elements can detach (especially when everything is hot) and diffuse into the steel. The chlorine/fluorine atoms work their way between the grain boundaries and un-stick them. A very small amount of chlorine can then cause a little crack at the metal surface, which opens up into a big crack when the metal is stretched.

We therefore exclude all materials containing chlorine or fluorine from coming into contact with the internal steel. Ideally we do not want them in the reactor at all, in case things come apart. This restriction unfortunately includes a surprising number of very useful engineering materials (e.g. some lubricants and many polymers, including plastic insulation tape).

Minimise Radioactive Waste

The inside of the reactor is *contaminated*. This is a technical term meaning that there may be a small amount of radioactive dust on the inside surfaces. It will probably be emitting alpha and beta radiation, and if ingested or breathed into the lungs it will irradiate the living tissue on the linings of the gut or the air passages, which are very sensitive to radiation damage, and may therefore cause cancer. Anything that goes inside the reactor and out again will be assumed to be contaminated. When it comes out it, either:

- it (or at least the contaminated outer surface) is disposed of as low-level radioactive waste;
- it must be cleaned. However, note that cleaning (for example, with swabs and cleaning fluid) also generates low-level waste (the dirty swabs and used fluid).

As an environmentally responsible organisation, we minimise all kind of waste – especially radioactive waste. It is also expensive to dispose of radioactive waste, so reducing waste is win-win. Designs for re-usable tools (e.g. manipulator arms or robots) need to be easily cleanable, or else be easily coverable by a disposable surface layer. (You sometimes see manipulator arms covered in polythene bags.)

Time

The reactor is already in a maintenance outage, and is cooling down. Towards the end of this period of two months we will remove a circulator for maintenance. (In real life you would have this time to design and build your recovery device. For CREST purposes the allowed time will be stretched because you are not working on the project full time.)

The circulator will be out of the reactor for three days. If your recovery takes longer than that (including any assembly, insertion, recovery, disassembly) you will delay the reactor output programme and cost EdF Energy £1m per day.

Quality and Safety

Safety is always the overriding priority. No one must be exposed to radioactivity. The reactor must not be damaged. You must show that you have considered how things might go wrong and what you have done to prevent it occurring. (You may, for example, identify the really critical steps where mistakes cause great problems, and declare that extra checking will be performed at that point. You may also use *redundancy* and *diversity* in your design. (Check the meaning of these terms from safety engineering on the Internet.)

The combination of time and quality/safety constraints means that you must certainly propose something that is good enough to succeed with a high probability, but you will probably not have time to design and build the ideal solution.

Even if you are doing pure science, waiting until you have designed the perfect apparatus before doing the crucial experiment will probably mean that someone else will make the important discovery first, with equipment *just* good enough to do the job. Learning to judge the right combination of effort, quality and time-to-completion in almost every field of human endeavour is an extremely important life skill – even including exam revision!

Teamwork

In the nuclear industry it is essential that everyone works as part of a team. Everyone checks what others are doing and we all encourage constructive criticism and advice. Anyone can say "STOP! I don't think that's right." We then listen carefully, discuss, and do not go on until everyone on the team is satisfied that the problem is resolved. (But that also means you must not be unnecessarily perverse or unreasonable: in a serious business everyone has to behave in a highly responsible way.)

Everyone on a team is important: some are good at having ideas – and others are good at seeing what is wrong with an idea. Some are good at organising – making sure that things get done when they need to be done. Some are good at starting things – others at finishing them off! You need to find out what your team members are good at, and then split the work between you. You need everyone.

You Must Produce a Report

Your report will need to:

- Explain your design proposal, and demonstrate that it will address all aspects of the problem scope, as described above. You should also argue the feasibility of the proposal: why you think that it can be built and successfully used in the time available.
- You must show that you have gone about solving the problem in a systematic way (for example, considering advantages and disadvantages of alternative possibilities).
- You need to think about the ways things might go wrong (e.g. something breaks), and how you would cope. Preferably, you should be able to argue, for example, that breaks will not occur because you have thought about what might cause a break and made the design strong enough for all conceivable forces. (Next time you fly on an airplane, think about the engineers who spent a lot of time worrying about this.)
- You should state the sources of information that you particularly rely on (for example, web sites used).

Design Questions

How will you get your device into the space, given the access restrictions? How do you get a long arm round a tight corner? How might you get a self-powered robot to where it could work?

How will you find the debris?

How will you pick it up and hold it securely?

How will you move with the debris? Can you manoeuvre an awkward shape through confined spaces?

Can you make something that has the strength required to pick up and hold a 500gm object that is also sufficiently small to get into the reactor?

Will the materials you select for construction be strong enough for the job?

How will these materials behave in the hostile environment of a reactor? Can they work at the target temperature? How will they behave under gamma irradiation?

How will you control the operations? (How will you see what is going on and send instructions – a two-way information flow?)

Where will you get the power to run your device from?

Can you store enough energy if you are using a self-powered device?

How will I get rid of radioactive contamination at the end of the job?

N.B. Engineers steal design ideas from anywhere they can. We try to learn from other peoples' mistakes!

The next page contains some links to start your research. Most of these will probably not work for this problem – but maybe they will stimulate ideas and perhaps you can adapt the designs. There are lots more ideas on the Web.

TRIZ - Inverse problem solving

Oxford Creativity is a commercial consultancy company who claim that creativity can be taught and learned. Much engineering problem solving comes from applying a small number of principles and mental tools. Lots of information on the TRIZ website is free and well worth a look, particularly the database of engineering design solutions – they certainly have one section on "picking up things".

http://www.triz.co.uk/index.php

http://www.triz.co.uk/cp12.php Access to the design ideas database is free.

http://www.triz.co.uk/pwpcontrol.php?pwpID=167 Tools

http://www.triz.co.uk/files/U48432_40_inventive_principles_with_examples.pdf This claims to be the 40 most important principles of creative problem solving.

Some general links on bio-mimicry

There is a lot of current interest in stealing design ideas from nature, which has had billions of years to evolve some really nifty design solutions.

http://biomimetic.pbworks.com/f/Biomimetics%E2%80%94using%20nature%20to%20inspire%20humanBar-Cohen.pdf

http://biomimetic.pbworks.com/f/Biomimetics%E2%80%94using%20nature%20to%20inspire%20humanBar-Cohen.pdf

http://171.66.127.193/content/3/9/471.full.pdf+html Biomimetics theory and practice.

http://pdf.aminer.org/000/354/913/new_mobility_system_based_on_elastic_energy_under_microgravity.pdf - A jumping robot!

This is facinating stuff – but remember that nature never invented the wheel (or gears) and had to manage without metal parts.

Octopus and Snake Bio-mimicry

"Soft" robotics is receiving a lot of attention in university engineering departments. Soft robots can squeeze into places "hard" robots cannot get to, and they may be harder to damage (or cause less damage to their environment).

A stand at Cheltenham Science Festival in June was demonstrating an octopus-like robot arm. It looks very interesting, though it is only for underwater robotics. (Still the idea is nice – and EdF also have Pressurised Water Reactors and store spent fuel underwater. Perhaps not for our current problem, but for the future.)

http://www.octopusproject.eu/index.html

http://www.octopusproject.eu/objectives.html

http://www.octopusproject.eu/files/OCTOPUS_BannerBio.pdf

http://www.octopusproject.eu/files/OCTOPUS_BannerRobot.pdf

Snake-bots are also receiving some attention, particularly for things like wriggling into buildings damaged by earthquakes and looking for survivors. This looks good for getting cameras to otherwise very inaccessible places. Could they be used to get something out? I don't know – but some of these types of device can be made from collections of small active modules that can be reconfigured to stick together into different shapes – not just snakes. This is real engineering *Lego*. I don't know if anyone has tried to design a robot that can reassemble itself while on the job – but what a research idea! Get yourself into a difficult space like a snake, turn into a different shape for the job, then get out again like a snake.

http://biorobotics.ri.cmu.edu/projects/modsnake/index.html

http://www.isi.edu/robots/conro/proto2SP.html