NUCLEAR TRAINING COURSE

COURSE 433

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November 1968 (R-2)

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NUCLEAR POWER

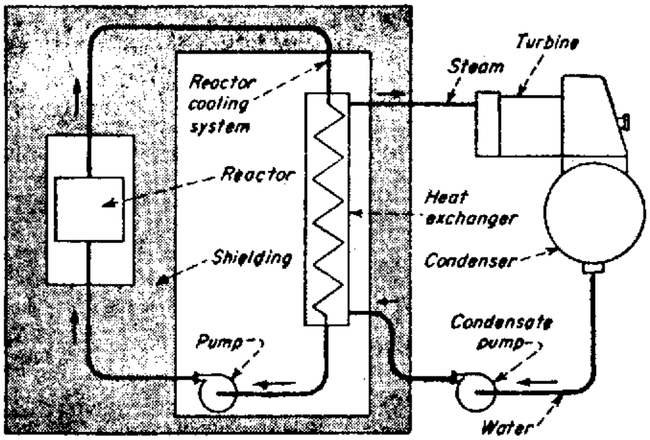
Nuclear power is being developed, not just as a cheap source of energy for the present, but also because available reserves of coal, oil and gas are definitely limited. An estimate of the future energy use and total amounts of fossil fuel which can be recovered at up to twice the present cost, indicates that the reserves will run out in about 100 years. There is, however, a potential of nearly 20 times this amount of energy in the world's resources of uranium from economically acceptable uranium ores.

Since there is a close tie between the energy consumption and standard of living in any country, there is a strong incentive to develop sources of energy as required to prevent a future energy shortage.

The lessons on Reactor-Boiler and Auxiliaries will describe the equipment and systems necessary to make use of uranium as a fuel and convert it into useful heat energy for steam generation.

Nuclear Power Stations

In a nuclear power station, the reactor can be compared to the furnace in a conventional station, not because they look the same, but because they both do the same job, supply heat. This heat can then be transferred in a heat exchanger to generate steam that can spin the rotor of a turbine-generator. The turbine-generator, condenser and pumps in the steam cycle are very similar to the equipment in a conventional station. Figure 1 shows a simplified circuit of a nuclear power plant.



A simple nuclear power plant has a reactor delivering heat to an exchanger to generate steam for a conventional turbine unit.

Fig. 1

Heat Generation from Fission

As noted previously, the purpose of the reactor in a nuclear power station is to supply heat. This heat results from fission and thus a basic understanding of fission and the chain reaction is fundamental to a study of nuclear reactors.

As studied previously, an atom consists of a nucleus made of neutrons and protons surrounded by electrons in various orbits. A free neutron has no charge and can penetrate into the nucleus of an atom without being affected by the negatively charged electrons or positively charged protons. If a neutron enters a mass of uranium and strikes the nucleus of a Uranium-235 atom, there is a certain probability that the nucleus will split (fission). This splitting or fissioning will release the enormous

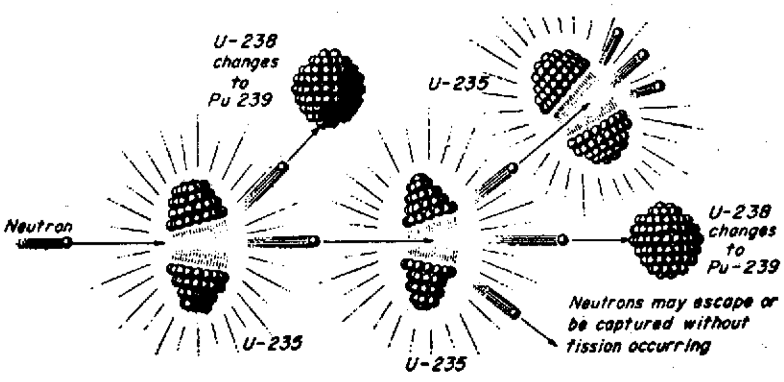


Fig. 2

amount of energy that binds the nucleus together to generate heat in the mass of uranium. In addition, the fissioned nucleus ejects two or three neutrons at high speed. These, in turn, charge through the uranium mass to heat and fission other nuclei. (Fig. 2)

This chain reaction can proceed (1) at explosive speed with the number of ejected neutrons multiplying infinitely, as in an atom bomb, or (2) at a controlled rate with the released neutrons building up to a certain level and remaining there, as in a reactor. An atom bomb, however, uses very concentrated U-235 (Uranium-235) extracted at great cost from natural uranium. A Canadian power reactor uses natural uranium, which contains only 0.7% of U-235.

With U-235 being the only natural fissionable material, it would appear that only 0.7% of natural uranium can be used. The U-238, however, has an important characteristic. If it absorbs a stray neutron, it changes after a delay of several days, into a new element, plutonium-239, which fissions just like U-235. Thus plutonium, not found in nature, is a man-made fissionable material. Also, U-238 can fission with neutrons of high energy level and contribute to the chain fission process to produce heat energy. This means that we can more nearly utilize all of the natural uranium as an energy source, not just 0.7%. We call U-238 a "fertile" material; - one that can be converted to a fissionable material.

Figure 2 shows U-235 atoms splitting into two new chemical elements (fission products) with the release of neutrons and heat energy. Therefore, in a nuclear reactor, the fuel is being constantly depleted and replaced by these "waste products" (fission products). These can act as a "poison" to the reactor, by wastefully absorbing neutrons and interfering with the chain reactions. One of the important fission products is Xenon-135 which absorbs a large number of neutrons.

Basic Reactor Components

Some of the terms used to describe major reactor components in these lessons are:

Fissionable Material and Fuel: Fissionable material is material whose atoms will split or fission when struck by a neutron and, as a result, release energy. The important fissionable materials in Canadian Reactors are Uranium-235 and Plutonium-239. Reactor fuel is an assembly or group of assemblies which have fissionable material contained in a metallic sheath.

Moderator: is the material which is used in the reactor to slow down neutrons so they will be effective in causing more fissions.

Heat Transport System: is the system which carries heat energy from the reactor fuel to the steam generator.

Reflector: is the material which surrounds the fuel and moderator and helps prevent escape of neutrons by bouncing them back into the core where they may cause fissions.

Shielding: is the material surrounding the reactor or any radioactive systems to reduce the escape of radiation to an acceptable working level for personnel.

Reactor Core: normally the material in the reactor vessel. This includes the fuel, moderator, and part of the heat transport system which is in the reactor vessel.

ASSIGNMENT

1. What is the main purpose of a reactor in a nuclear power station?

2. Why is it important that additional neutrons are released when an atom fissions?

3. What is the purpose of:

    (a) the moderator?

    (b) the heat transport system?

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POWER REACTOR CONSTRUCTION

There are many different concepts for power reactors and even within the field of heavy water moderated, natural uranium fuelled reactors, there are many possible variations in design and construction. There are many common problems in the various methods used as well as special problems with each type that may require materials and systems not found in conventional stations. This lesson will introduce some of the variations and briefly discuss the basic objectives in the design.

Objectives in Reactor Construction

It has already been noted that the function of a reactor is to act as a furnace in the nuclear power station, that is, it must supply heat energy. The next step is to consider the basic objectives in how this energy is supplied without going into any details of the systems involved.

As an extreme case let us first consider the heat produced by a typical research reactor. Here the reactor may be cooled by water from a river or lake which enters the plant at say 50°F and leaves at less than 200°F. A great deal of heat may be removed this way but it is evident that this heat is of little or no use in a power station since these temperatures would not produce steam even at atmospheric pressure. To make this heat useful it must be available at a higher temperature and we now have our first objective: The heat supplied by the reactor must be at a reasonably high temperature (normally a minimum of 400 to 500°F).

The details of the neutron cycle and its effect on the chain reaction will not be dealt with in the level 4 lessons, but some understanding of the effect of neutron losses is necessary. Since the source of heat in the reactor is the fissions which occur in the chain reaction, it is obvious that there must be enough neutrons available to maintain the chain reaction.

Two ways in which neutrons can be wastefully lost is by capture in the structural materials in the reactor and by escape from the reactor. If these are both kept to a minimum, then the chain reaction can be maintained even with fuel which has already given up a lot of energy from many fissions. This allows us to obtain the maximum energy from the fuel. Our second objective can therefore be stated: The reactor should be designed so that the maximum amount of heat energy can be obtained from the fuel.

Reactor Materials

Steel is the most common metallic structural material and finds many uses in reactor construction as elsewhere in industry. There are many different types of steel available depending upon the amounts of alloying materials present and, for example, if the application justifies the extra expense, corrosion resistant stainless steel could be used rather than a normal carbon steel. One major problem is encountered, however, when steel is to be used as a construction material in the reactor core. We noted previously that one of the major objectives was to keep neutron losses to a minimum and unfortunately, the iron in steel captures a relatively large number of neutrons. This almost eliminates steel from any use in the central part of the core, although the outer wall of the vessel may be made of steel without excessive neutron capture.

Other materials which are commonly used to improve the neutron loss situation are aluminum and zirconium or zirconium alloys (zircalloy). Aluminum is relatively cheap, and is quite useful, but does not stand up to high temperature. Since we require the heat energy to be at high temperature, the use of aluminum is limited. This has led to the development of zirconium alloys which are satisfactory in strength, neutron capture and temperature effects, and are therefore, commonly used for construction materials in the reactor core.

Figure 1 shows the relative neutron losses in passing through a piece of steel, aluminum or zirconium.

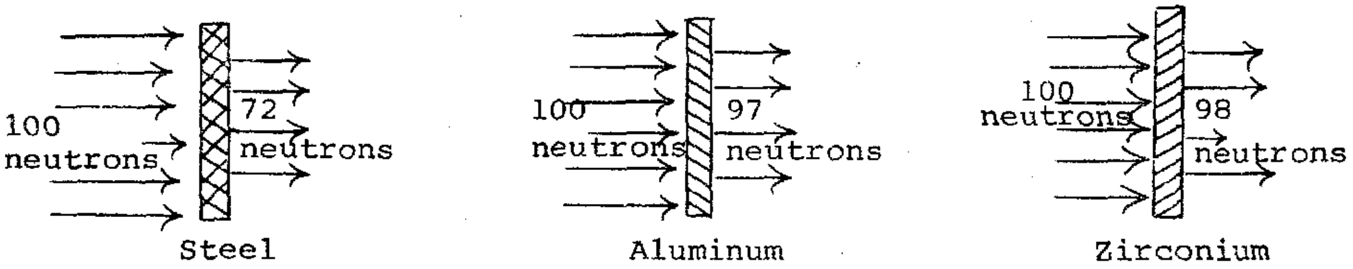

Fig. 1

Pressure Vessels and Pressure Tubes

The various materials used for moderators and heat transport fluids will be discussed in later lessons but one common material is water. Since water boils at 212°F at atmospheric pressure and we have said that the heat energy must be removed at 400 to 500°F to be efficient, then we must pressurize the water to prevent boiling at low temperatures. This high pressure water can be contained either in a high pressure vessel or in pressure tubes which run through a low pressure vessel.

A simple pressure vessel is shown in Figure 2. In this case, both the moderator and heat transport fluid are heavy water which flows first into the moderator region and then over the fuel carrying away the heat generated. The whole core is at high pressure and therefore, only thin walled tubes are required to guide the water over the fuel. The use of thin walled tubes keeps the neutron losses due to capture to a minimum. This type of system is most advantageous when the same liquid is used in both moderator and heat transport systems. If, for example, a reactor had D_2O moderator and H_2O heat transport system, it would be difficult to keep the two systems at the same pressure so as not to overstress the thin tubes. An even more important limitation on the pressure vessel when used with natural uranium is the difficulty in fabricating large pressure vessels. With presently available equipment, it is only possible to make pressure vessels large enough to result in about 100mw electrical output. This is not compatible with Canadian plans which call for stations of about 400-500mw electrical as a minimum economical size.

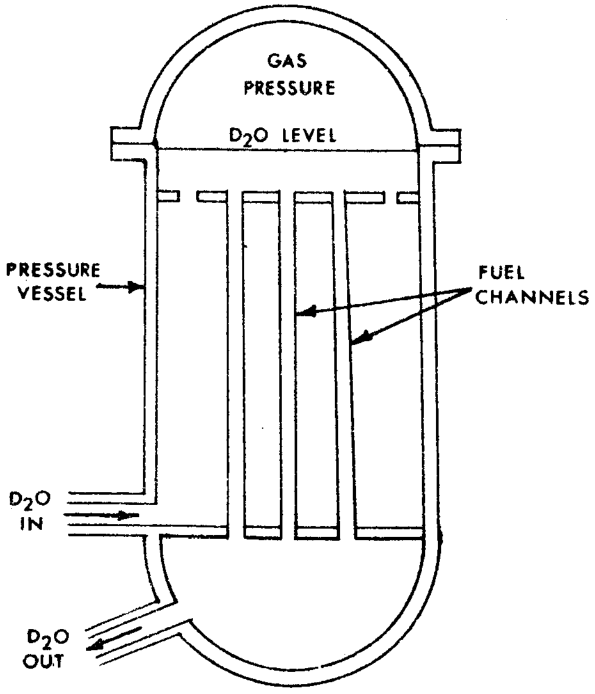

Fig. 2

The pressure tube type of design uses a low pressure calandria which serves as a container for the moderator.

A calandria is a vessel with a bundle of tubes running through it and could be field-erected of relatively thin material to any desired size. High pressure tubes which carry the heat transport fluid are then run through the calandria tubes. A simple reactor of this type is shown in Fig. 3.

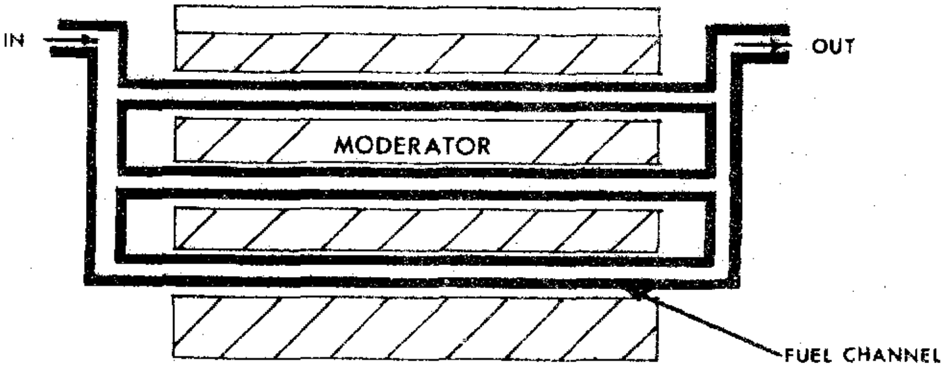

Fig. 3

In this case, the moderator would be D_2O but the coolant could be any other fluid without difficulty in keeping them separate, since the pressure tubes obviously give complete separation. The presence of the pressure tubes in the reactor core means there is more material which will capture neutrons unproductively and a material must be chosen which does not capture too many neutrons. As a result, zirconium alloys are often used as pressure tubes.

This design overcomes the main objection to pressure vessels, that is, size is not seriously limited. If a reactor is to be made larger, it is not difficult to simply add more pressure tubes and because the calandria is a relatively low pressure vessel, it can also be fabricated in larger sizes.

ASSIGNMENT

1. What are the two main objectives in reactor construction?
2. Why would zirconium be used as a structural material in a reactor when steel is cheaper and just as strong?
3. What is the main objection to developing natural uranium, pressure vessel reactors for the Ontario Hydro system?

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MODERATOR SYSTEMS

The lessons on fission in the nuclear theory course explained that Uranium-235 can be most efficiently fissioned by slow or thermal neutrons. Since the neutrons given off at fission are fast neutrons, some method of slowing down is required. This slowing down process is called <u>Moderation</u> and the material used to do it is called a <u>Moderator.</u> The materials which are normally considered to be moderators are light water, heavy water, graphite and beryllium. These materials will be briefly discussed and then more detail given to the requirements of a heavy water moderator system since this is the only moderator presently proposed for use in the Canadian nuclear power program.

Moderator Materials

<u>Light water</u> is attractive as a moderator because of its availability and low cost even in a very pure state. It is also very good at slowing neutrons down, but unfortunately, also captures a large number of neutrons at it slows them down. This loss of neutrons is so large that it is not possible to maintain a chain reaction with light water and natural uranium.

<u>Beryllium</u> and its oxide (ie, beryllium combined with oxygen to make a compound) are good moderators. In spite of many technical advances in the past few years, beryllium is still an expensive metal and is bodily attached by air and water at light temperatures. It is therefore, used only in very special or experimental designs.

<u>Carbon</u> in the form of graphite blocks, has been used as a moderator in a number of natural uranium reactors, particularly in the United Kingdom. Carbon is relatively cheap and easily machined, but its moderating properties are only mediocre and it therefore, requires a very large reactor core.

<u>Heavy water</u> is by far the best moderating material available It slows down neutrons quickly and captures very few of them. Very satisfactory performance is obtained with natural uranium and it has no serious undesirable effects in a low pressure system. It can also be used as a heat transport fluid but then of course, must be pressurized to prevent boiling. The only serious fault of

heavy water is its cost. At present, it is worth approximately \$28 per pound which results in a 8¼ million dollar expenditure for the moderator material in a station like Douglas Point.

The Heavy Water Moderator Circuit

The high cost of heavy water does not end with the initial purchase, but must also be considered in connection with losses from any heavy water system. The effort made to minimize and recover leakage is apparent throughout the system and must be considered for each new piece of equipment.

One of the main reasons for having a moderator system or circuit, rather than just filling the reactor vessel and leaving it stagnate, is that considerable heat is generated in the moderator. This heat comes from the effects of nuclear radiation on the water, plus heat transferred from the hotter heat transport system. The total heat generation in the moderator is typically about 6 or 7% of the reactor thermal output. This would quickly boil the heavy water if it were not cooled. The simplest type of circuit is shown in Figure 1 and consists only of a pump, a heat exchanger and associated piping. As noted above, this circuit will be as leak-proof as possible, with most joints welded and possibly double seals on the pump shafts and heat exchanger tubes. There will also be some detection system which will alarm if leakage is detected.

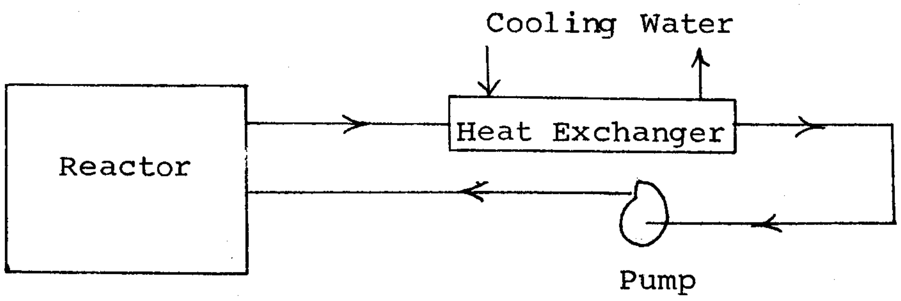

Fig. 1

The circuit materials may vary, but the various materials which are used in the circuit must be compatible. For example, if aluminum is used in part of the calandria (remember from the previous lesson that aluminum is acceptable in the core because it does not capture too many neutrons) then neither mild steel nor copper can be used elsewhere in the circuit. The reason for this, is that the water chemistry which prevents corrosion with mild steel is quite different than the correct chemistry for aluminum, while the presence of copper on the other hand can cause deterioration of the aluminum.

The heavy water becomes radioactive while it is in the reactor core and the system equipment must therefore, be shielded. The two main sources of radioactivity are N-16 and 0-19 which are formed in the water. Fortunately, these isotopes both have very short half-lives and disappear a few minutes after the reactor is shut down. This means that while shielding is necessary during operation, when the reactor is shut down, the equipment can be worked on without receiving high radiation exposures. Some protection is needed, however, to prevent the internal uptake of tritium (H-3). The problems of working with tritium in heavy water are dealt with in detail in the radiation protection and procedures training.

The moderator system may also be used to either control the reactor by varying the level in the reactor, or to shut down the reactor by dumping out the moderator. This of course, requires additional equipment, such as a tank into which the moderator can be dumped, but these will not be dealt with in the level 4 lessons.

ASSIGNMENT

1. Since heavy water is much more expensive, why is it used for a moderator instead of light water?
2. Why is a cooling circuit necessary for a moderator?
3. When can maintenance work be done around a moderator pump?

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HEAT TRANSPORT SYSTEMS

There is a fairly large variety of materials which can be used in heat transport systems, and there is no clear advantage for any one, although each may have particular advantages and disadvantages keeping in mind the two objectives of reactor construction given in a previous lesson. The first of these objectives was that the reactor produce heat at high temperature. Since the main job of the heat transport system is to carry heat from the reactor to the boiler, it must capable of doing so at high temperature. The second objective was to obtain the maximum amount of energy from the fuel which implies, keeping neutron losses to a minimum. The heat transport system must therefore, capture as few neutrons as possible while it passes through the reactor.

Various materials which have been used in heat transfer systems will be reviewed, and the type of system associated with each will be discussed. Emphasis will again be given to the materials which are used or proposed for Canadian nuclear power stations.

Heat Transfer Materials

Water is the most common heat transfer material in the Canadian nuclear program, and may be used in a number of forms. First of all, a choice must be made between light and heavy water and either of these may be used as liquid, steam or fog (steam which has water droplets in it). In discussing moderators, we noted that light water would not sustain a chain reaction with natural uranium because it captured too many neutrons. The capture of neutrons is still important, and is a strong factor in favour of heavy water, but because the volume of heat transport fluid in the reactor is much less than the volume of moderator, light water cannot be ruled out in this case. This is particularly true, if the systems uses steam or fog, so that due to lower density, there are fewer pounds of water in the core. A disadvantage of any water system is that it must operate at high pressure (at least 1000 psi) in order to obtain high temperature. The high pressures make the leakage problem worse and gives a factor in favour of light water which is much cheaper.

Organics, which are compounds made of hydrogen and carbon similar to wax, may be used to transfer heat in a nuclear station. The heat removal or carrying properties of these materials are not nearly as good as water, but they have a much higher boiling point. This allows operation at high temperature without much pressurization. Organics also have disadvantages in that they form tars under irradiation, and leaks are both toxic and highly flammable (may even ignite spontaneously).

Liquid metal such as sodium or sodium-potassium are used in some cases because of good heat transfer properties and no need for pressurization. Sodium however, becomes highly radioactive in the reactor, and the system must be kept shielded for approximately 2 weeks after shutdown. It also reacts violently with water, and hence care must be exercised in the design of sodium-water boilers. One further disadvantage for a large natural uranium reactor is the relatively large number of neutrons it captures. This type of heat transfer material is only likely to be found in enriched reactors which have small cores.

Gases are inherently poor heat-transfer agents because of their low density compared to liquids. This difficulty can be overcome to some degree by operating the gas at high pressure, but this creates other problems. The low density also makes pumping difficult and a large amount of power is required to drive the necessary pumps. The main advantage of gases are their ability to operate at high temperatures. Some gases, such as helium, create no corrosion problems at high temperatures, and hence extend the life of the system components and possibly the fuel.

Direct and Indirect Cycles

The most common type of heat transport system is one which carries the heat produced in the reactor to a boiler where light water is boiled and the steam used in a conventional turbine cycle. This is known as an indirect cycle since there are two steps. It is also possible, however, to heat a gas, or boil water in a reactor to form steam, then take the gas directly to the turbine. This is known as a direct cycle. Schematic drawings of both are shown in Figure 1.

The direct cycle appears somewhat simpler since it eliminates the boiler, and it also eliminates the temperature drop which occurs in the boiler, giving more efficient operation. It has a number of difficulties, however, some of which are:

1. It is difficult to construct the pressure tubes in the reactor and the fuel so that they will stand the boiling and partial steam conditions without problems of corrosion.

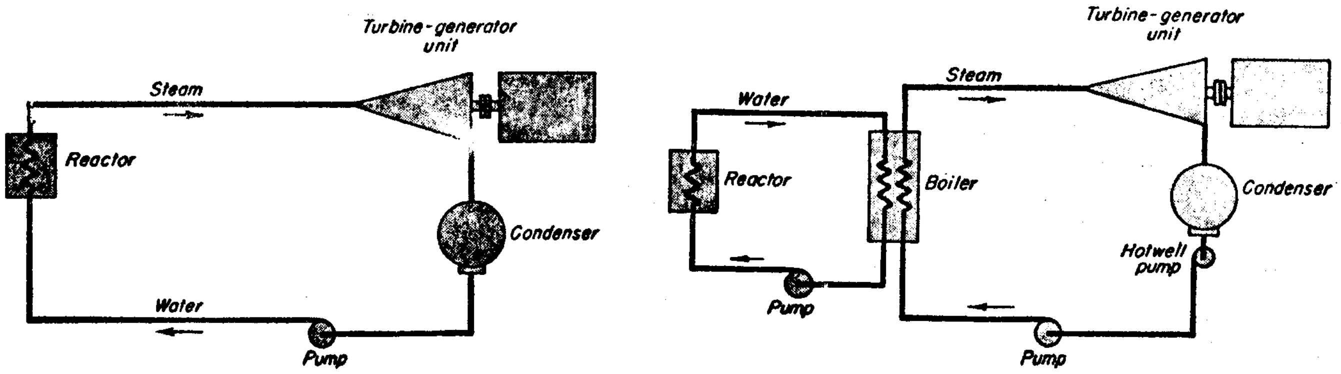
2. The turbine and associated equipment will require shielding due to radioactive material formed in the reactor.

3. If heavy water is used, in-leakage in the condenser and other low pressure areas of the system will carry in light water and down grade the heavy water.

4. The turbine and its auxiliaries will become contaminated with radioactive material and any out leakage will up-read contamination.

The indirect cycle allows the use of ordinary water in the turbine cycle combined with any of the heat transport materials discussed previously. This results in the advantage of standard equipment for the turbine and auxiliaries. The indirect cycle loses efficiency since the temperature of the turbine cycle is lower than whatever heat transport temperature is permissible due to the temperature drop in the steam generator.

Most power reactors presently use an indirect cycle, but as the problems associated with boiling and steam cooling are overcome, there is likely to be a swing towards direct cycles.



Direct Cycle Fig. 1 Indirect Cycle

Heat Transport System Components

The heart of system is the section passing through the reactor since it must meet special conditions and is extremely difficult to repair. Both pressure tubes and pressure vessels were discussed in the earlier lesson on reactor construction and it was noted that the pressure tube design was the most promising for large natural uranium stations. There must also of course be piping external to the reactor to carry the heat transport fluid and a pumping system to circulate it. If we consider an indirect cycle, a boiler must be added, which will have a heat exchanger as part of the heat transport system.

As with a moderator system, the materials used in the heat transport system must be compatible. The most common pressure tube material for a natural uranium reactor is a zirconium alloy (zircaloy) which can be used with a carbon steel piping system. More expensive materials such as stainless steel may still be used for special applications in valves, etc, where long life and high reliability of operation is required.

Leakage may be a very important consideration in choosing components or methods of construction. This is particularly important in the case of heavy water which is very expensive. A heavy water system will have the majority of joints welded, and will use double seals whenever possible on pump shafts, valve stems, heat exchanger joints etc. As well as the effort to prevent leakage, there will be associated systems to detect and recover losses. The detection devices may include level switches or probes in collection tanks or trays, indicators which visibly change when wetted or instruments, which detect increased vapour or activity in the air. The recovery systems are normally a part of the ventilation and drainage systems. Leakage may also be very important in a liquid metal system. The most common liquid metal used is sodium which reacts violently with light water. This makes leakage between the sodium and the water in a boiler most undesirable.

The main circulating pumps in a heat transport system represent not only a fairly large initial investment, but also require from 2 to 3% of the net output of a large station during normal operation. There are a number of ways in which these expenses can be minimized. It has already been noted that materials such as gas and organics require more pumping power than water. The size of the piping can also influence pumping power which would become excessive, if the piping was made too small. The initial cost of the pumps can vary considerably, and a balance must be reached between attempts to keep the cost down and obtaining reliable pumps which will not require excessive maintenance.

ASSIGNMENT

1. Why is it possible to use light water as a heat transport material in a natural uranium reactor when it cannot be used as a moderator?

2. Why must a heat transport system using water operate at high pressure?

3. Give two advantages of a direct cycle over an indirect cycle.

4. Given the following information:

   (a) heavy water cost = $28/lb
   (b) 1 drop/sec = 20 lb/day

   Calculate the cost of replacing the heavy water from a leak of 2 drops per sec which is not repaired for 4 months.

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AUXILIARY CIRCUITS

In addition to the main reactor systems which are primarily responsible for the production and transfer of heat, a number of auxiliary systems are generally present to support the main systems or serve special purposes. Some of these are present to remove heat caused by radiation capture, others to control the chemistry of main systems and still others for safety reasons.

Some of the most common reactor auxiliary systems will be briefly described in this lesson.

Reflectors and Reflector Cooling

The reflector was defined in an earlier lesson as a material surrounding the reactor core which prevented neutron losses by bouncing (or reflecting) neutrons back into the core. We have since studied moderators and learned that a moderator must be able to slow neutrons down quickly without capturing too many. In general, materials which make good moderators, also make satisfactory reflectors, but the requirements are not so stringent. For example, light water cannot be used as a moderator with natural uranium because of its neutron capture, but it is satisfactory as a reflector. Other materials which may be found as reflectors include heavy water, carbon (graphite) and in special cases, beryllium. If water is used, it must, of course, be contained in a vessel around the core, and the materials used to make the vessel must be acceptable for reactor core construction as discussed in an earlier lesson. This is sometimes simplified by making the moderator vessel bigger than the fuel core, so that the outer part of the moderator in the vessel acts as a reflector.

If a separate reflector is used, a method of cooling is required, since the capture of radiation in the reflector material causes heating. The heat removal system will depend upon the material chosen for the reflector. A liquid reflector can be circulated through a heat exchanger and cooled in a manner similar to a moderator system. A solid reflector material such as graphite must be cooled by circulating a coolant in embedded pipes or by blowing a gas coolant over the graphite blocks.

Shield Cooling

Due to the radiation released in a reactor, both at the time of fission and as the fission products decay, a heavy shield is required to protect personnel. The main part of this shield is often a thick concrete wall. As the radiation is stopped by the shield, the energy of the radiation is changed to heat. At the inner surface of the shield where the radiation is most intense, the heat produced would cause excessive temperature if some method of cooling is not supplied.

As well as producing stresses which could lead to mechanical failure, high temperatures in a concrete shield will drive out retained water, and hence reduce the shield's effectiveness.

The most common cooling system is to embed pipes near the inner surface of the shield, and use a pump to circulate water through the embedded pipes and a heat exchanger.

Demineralizer Systems

In any of the systems where water is recirculated, there is likely to be a demineralizer or chemical control auxiliary circuit. This is normally a small parallel circuit containing one or more ion exchange columns and possibly a filter. An exception to this is the chemical control equipment for the boiler system which will be discussed in a later lesson. The purpose of a filter is obviously to filter out particulate matter down to some acceptable size of particle. Various types of filters can be purchased depending upon the degree of filtering required. As a general rule, the cost increases (either due to initial cost or more frequent replacement) as the size of particle which must be removed, is reduced. A filter is normally located up-stream from the ion exchange columns to prevent plugging of the columns.

The action of an ion exchange column will be described in more detail in lessons you will take later in chemistry, and for the present, we will only describe the general results obtained. Some materials may dissolve in the system, and exist in the in the form of individual molecules. These can obviously not be filtered out by mechanical means, but can effect the chemistry of the system. This can include such things as corrosion products from the system components, or products formed from gases which are picked up from the air. For example, under some conditions, nitrogen from the air can lead to the formation of nitric acid which is very harmful to most systems and must be removed. This type of impurity is very effectively removed by ion exchange columns. After a period of time, a column may become so loaded with impurities, that it cannot remove any more. The column is then said to be spent and must be replaced. In some cases, columns can be "regenerated", in which case replacement with a new column is not necessary.

Dousing and Containment Systems

One of the main considerations in analysing the safety of a nuclear station is the question of whether or not large amounts of radioactive material could escape from the site following a major (even if almost impossible) accident. Various systems have been used to help ensure that any major activity release will remain on the site. One of the methods which has been used in a number of nuclear stations in the U.S.A., is to construct a containment shell around the whole reactor building. This is large, often spherical building, which is evident in pictures of some American stations. This approach is very expensive, since the shell is very large and must be constructed to stand whatever pressure is considered to be maximum in a major accident.

In the Canadian program, a different approach to the containment problem has been adopted. This approach is based on the following factors:

1. In a heavy water moderator and water cooled reactor, the pressure surge following an accident is due , almost entirely, to steam formation.

2. The initial release of steam will occur before any significant fuel failures and will, therefore, contain very little radioactive material.

Based on these factors, a method is used which will control the pressure below that which would damage the normal building required. A relief system may be supplied which will vent the initial burst of non-radioactive steam and then return to the sealed condition.

A large supply of water from a reliable source (such as a large storage tank) is then sprayed into the area which contains the steam. This water spray condenses the steam, and hence lowers the pressure. This dousing action has led to the name dousing system for this equipment.

The system will typically include a water storage tank, large lines with power operated valves, and spray nozzles or tanks in the area where a steam leak may occur. One of the important considerations in the design of this type of system is the need for testing. Since it is a safety system, some assurance of reliability is required, and at the same time, there is a high probability that it will never be operated in the life of the station. Long idle periods can lead to valves sticking, etc, so it is normal to test the valves at regular intervals, say once or twice a year. This means that two valves have to be installed in each line so that any valve can be tested without releasing the water.

ASSIGNMENT

1. What is the purpose of a reflector?
2. Why is it necessary to supply cooling to the inner part of the bulk shield?
3. An ion exchange column will act effectively as a filter. Why then is a filter often installed up-stream of the ion exchange column?
4. Give two examples of things an ion exchange column might remove from a water circuit.
5. What is the purpose of a dousing system?

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FUEL

The fuel in a reactor is the source of heat, but in producing the heat, it is not "consumed" in the same sense as burning fossil fuel. From basic nuclear physics, we know that the heat released in the reactor fuel, is due to the decrease in mass during the fission process. However, the total decrease in mass for a fuel slug coming from a power reactor is only about 1%, so that the weight before irradiation is roughly equal to the weight after irradiation. Aside from the possibility of some deformities such as wrinkles or bowing, the majority of fuel removed from the reactor will look just like the fuel which is being put into the reactor. The main difference is that the spent fuel is highly radioactive, so that a person handling fuel 1 hour after removal from the reactor, would receive a lethal dose in 30 to 40 seconds, if no shielding were provided. This time would be reduced to 2 to 3 seconds for fuel taken directly from the centre of the central channels in a reactor.

Fuel Materials

The fuel material must be one which will fission readily under neutron bombardment. The most common material (and only naturally occurring fuel) is Uranium-235. Only 0.7% of natural uranium is U-235 and the remaining 99.3% is U-238 which does not fission readily. As a result, there are many neutrons lost by capture in U-238 in a reactor using natural uranium fuel. This capture occurs most often when the neutrons have an intermediate energy, that is, whey they are partially slowed down from fast to thermal energies. You will recall, from the lesson on moderators, that one desirable property of a moderator was to slow down neutrons quickly. This is because they will not remain too long at intermediate energies, where capture in U-238 is most likely. Fortunately, these captures in U-238 produce U-239 which decays radioactively, to Plutonium-239 (Pu-239), another fuel material. The Pu-239 will then fission if struck by a neutron and thus add to the heat energy produced by the fuel.

When natural uranium is used as the fuel material, it may be in the form of pure uranium metal, metal alloys, uranium carbide or uranium oxide. The metal has the advantages of having no added neutron absorbers, and the maximum density. These properties result in uranium metal being the best fuel with respect to maintaining the chain reaction. However, pure uranium metal distorts under irradiation and reacts quickly with hot water, so that it is not normally used in power reactors. Adding an alloy to the uranium will improve on these disadvantages, but the alloying materials then wastefully capture neutrons. This waste of neutrons would probably result in a necessity to use uranium which has been ENRICHED, ie, the concentration of U-235 has been artificially increased above 0.7%. The equipment required to enrich fuel is extremely expensive and, at present, is used only in the U.S.A. on a large scale. A better method is to use uranium oxide or uranium carbide which are stable materials, and can still be used as natural uranium. The most common power reactor fuel at present is uranium di-oxide (UO_2).

Sheathing Materials

The fuel must be enclosed in a sheath to hold the fuel together, and prevent the radioactive fission products from escaping into the heat transport system. This sheathing material must meet approximately the same requirements as the reactor pressure tubes which were discussed in an earlier lesson. That is, they must stand the high temperatures and pressures without failure or serious corrosion, and they should capture a minimum number of neutrons. Again stainless steel would be a good choice if it were not for excessive neutron capture. For a natural uranium reactor, other materials are required, and the most common material in Canadian designs is a zirconium alloy. Even with zirconium which doesn't capture too many neutrons, there is still a strong incentive to keep this material to a minimum. This results in using a sheath which is as thin as possible without having too many failures in the reactor. At present, fuel sheathing is generally about 0.015 inches thick.

Fuel Fabrication

As well as choosing the materials to be used in the fuel, it is necessary to decide on the shape and size of the fuel. Some of the shapes which have been used are shown in Fig. 1.

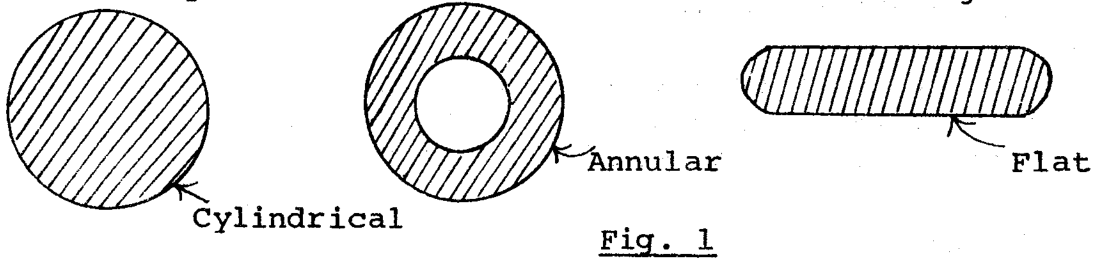

Fig. 1

The annular shape is rather difficult to fabricate and the sheathing material on the flat is inclined to bulge under pressure and eventually fail. The most common shape is therefore, the cylinder which is a stable, easily fabricated shape.

If we decide to use the cylindrical shape, we must now decide upon the size of each ELEMENT. If the size of the pressure tube has been fixed, the fuel could be made in one single element with the coolant around the outside only, or it could be divided into a BUNDLE of several elements as shown in Figure 2.

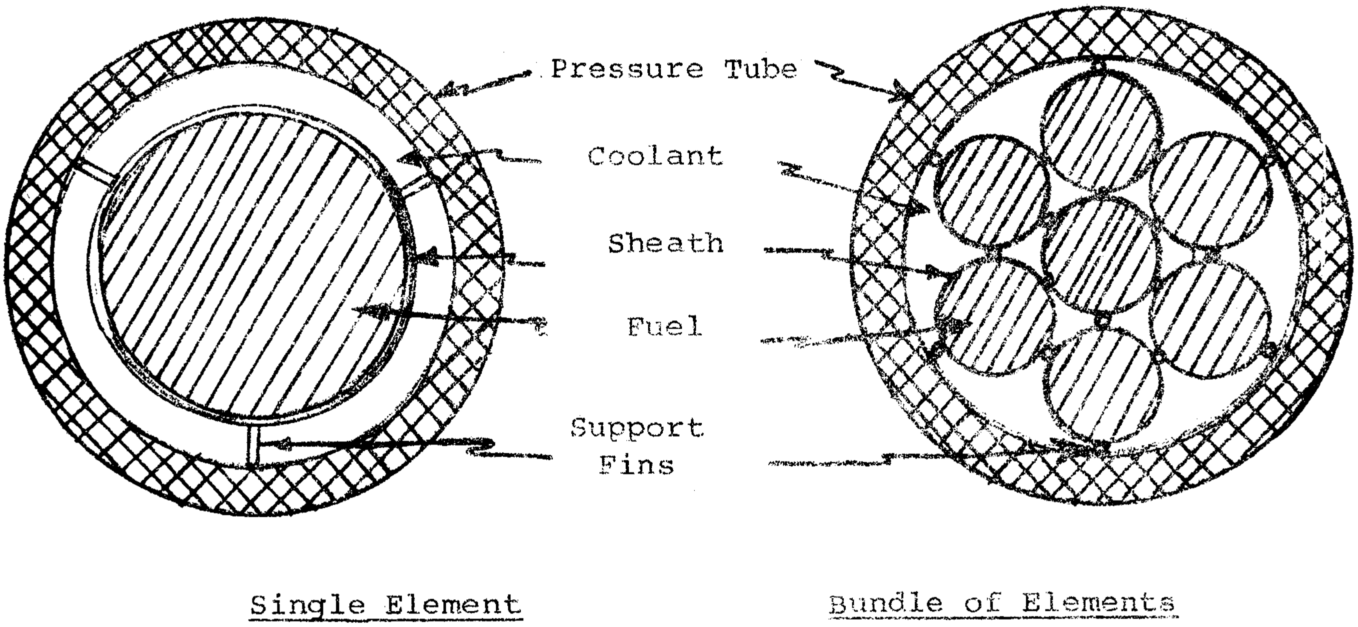

Fig. 2

The reason some cross-sectional subdivision may be required, is to improve the heat removal from the fuel. The centre of the single element in Figure 2 will be hotter than the centre of any of the smaller elements for the same total heat production, since the heat has to be transferred along a longer path. This central temperature in a large fuel element at high power would likely exceed the temperature at which damage occurs. Subdivision must be kept to a minimum, however, since increased subdivision introduces more sheathing material for the same amount of fuel. For example, if we consider Figure 2 and make the diameter of the large element 2.65" and the diameter of the seven small elements 1", then the cross-sectional areas are:

Single Element

$$A = \frac{\pi d^2}{4} = \frac{3.14 \times 2.65^2}{4}$$

$$= 5.5 \text{ sq in}$$

7- Element

$$\text{Area} = \frac{7\pi d^2}{4} = \frac{7 \times 3.14 \times 1^2}{4}$$

$$= 5.5 \text{ sq in}$$

The amount of fuel is therefore, the same in each case. The amount of sheathing however, depends on the total circumference, which is:

Single Element

$$C = \pi d = 3.14 \times 2.65$$

$$= 8.3 \text{ in}$$

7-Element

$$C = 7\pi d = 7 \times 3.14 \times 1$$

$$= 22 \text{ in}$$

We have therefore, increased the amount of sheathing by nearly three times by subdividing from a single element to 7 elements.

Cross-sectional subdivision may therefore, be summarized as follows:

1. Subdivision is an advantage from the point of view of heat removal. Some subdivision in power reactor fuel is nearly always required for this reason.

2. Subdivision is a disadvantage because it introduces extra sheathing material which captures neutrons. For this reason, it should be kept to a minimum, compatible with the requirement noted above.

It may also be necessary to divide the fuel into short bundles rather than one which extends the full length of the channel. This will make the handling easier, and the fuelling machine smaller. As in the case of cross-sectional subdivision, the number of bundles per channel should be kept to a minimum so that extra structural material (such as end caps at the end of each element) is not added to the reactor.

ASSIGNMENT

1. Is any benefit obtained from the neutrons captured in U-238 and if so, what is it?

2. What are two disadvantages of uranium metal as a fuel?

3. Is stainless steel a good material for natural uranium fuel sheaths and why?

4. What is the reason for cross-sectional subdivision of reactor fuel and why should it be kept to a minimum?

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FUEL HANDLING AND STORAGE

There are three general divisions of fuel handling and storage which must be considered. These are:

1. New fuel handling and storage
2. Reactor fuelling
3. Spent fuel handling and storage

A separate lesson on reactor fuelling will be given later which will cover this section in more details than given here.

The details of the handling problems in the three general areas mentioned above are quite different, since the fuel becomes highly radioactive while in the reactor. In all three areas, however, it should be kept in mind that the fuel is expensive and rather delicate. It was noted in the earlier lesson on fuel, that it is desirable to keep structural materials in the fuel to a minimum, so that a minimum number of neutrons are captured. This results in fuel assemblies which have a very small factor of safety in structural strength to allow for any "rough" handling. Coupled with the fact that fuel is easily damaged, is the rather high economic penalty involved for any fuel which either cannot be used or causes difficulty in remote handling equipment.

The fuel assembly is likely to be worth at least $1000. This is small compared to what might be spent if the fuel became jammed somewhere between the time when it goes to the reactor and when it arrives in the spent fuel bay.

New Fuel Handling and Storage

Under normal conditions, the new fuel which is received at a generating station will be free of contamination and have such a low level of radioactivity, that it presents no hazard for any type of handling. The two main problems, then, are to prevent physical damage to the fuel which would adversely affect its future performance, and to keep correct inventory records if a large number of fuel assemblies are involved.

The first operation on receipt of the fuel will be an inspection to determine whether or not the fuel is acceptable. This will be necessary, since one shipment of fuel will ordinarily last for a period longer than the manufacturer would be willing to wait for payment, and the buyer would be reluctant to make payment until he has some assurance that the fuel is in good condition. The fuel is then moved to a new fuel storage facility, where it must be protected from damage due to personnel working in the area, and also from moisture and dirt. When the fuel is taken from storage, it should be inspected again before going to the reactor. This inspection should be even more detailed than the acceptance inspection, so that no faulty fuel is installed in the reactor. The final operation will be to load the fuel into a facility which starts the refuelling operation. It may be necessary to make records of each of these operations to keep an accurate inventory.

It is difficult to put too much emphasis on the care which must be taken in handling new fuel, since this is a routine operation, and there may be some tendency to become careless. Even damage which is not noticeable (such as a cracked weld) could have very serious consequences if it results in mechanical failure while the fuel is in the reactor or fuel changing equipment.

Reactor Fuelling

The reactor fuelling is generally carried out by one or two fuelling machines. A single machine will likely be used if the reactor channels are fuelled from one end only, but if the fuel is pushed in one end and out of the other, a machine is needed at each end. Since the machine must handle the irradiated fuel in moving it from the reactor to the fuel bay, some shielding must be supplied. This may either be built into the machine (in which case the machine is accessible) or the machine may be located in a shielded room and operated by remote control. Aside from the shielding problem, the size and complexity of the machine will depend largely on the type of heat transport system and whether fuelling is done "on-power" or during shutdown. On-power refuelling gives an economic advantage in that the fuelling costs are lower due to obtaining more heat energy from the fuel. This advantage is partially offset by the increased costs associated with an on-power machine.

Spent Fuel Handling and Storage

The main consideration in handling and storing spent fuel, is the control of radioactivity and contamination. The general principles used to control these, are to shield against the radioactivity, and to enclose the fuel in a container to prevent the spread of contamination.

The most common way of handling and storing spent fuel, is in a water filled bay or trench. (The fuel must, of course, be moved from the reactor to the bay in the refuelling operation.) About 15 feet of water is generally used as shielding, which gives a gamma ray attenuation of about 10^{10}. This is sufficient for fully irradiated fuel which has just been removed from the reactor. If the fuel is to be removed from the bay, it may be loaded under-water into a flask which is shielded with iron or lead.

If the fuel sheath has no defects, it will control the spread of contamination without further canning, but the effects of corrosion must be considered for long term storage. You will recall from the lesson on fuel, that the sheath is designed so that it is as thin as possible without too much danger of failure in the reactor. This means that there is a possibility of corroding through the sheath rather quickly if the bay water chemistry is not carefully controlled. It may turn out to be cheaper (and more reliable) to seal all fuel in heavier walled cans rather than to install and operate elaborate bay water purification systems. Any fuel which has ruptured in the reactor or during spent fuel handling should, of course, be canned as quickly as possible to prevent excessive contamination of bay water.

Since the development of reactors and reactor fuel is at a very early stage, there is considerable interest in fuel performance. One of the methods used to check the performance, is to examine the spent fuel to determine dimensional changes or defects which have developed in the reactor. It is, therefore, important that the spent fuel be handled carefully, so that handling damage does not mask irradiation changes.

ASSIGNMENT

1. Give two general results of mishandling new fuel which have a rather large economic penalty.
2. What is the main advantage of on-power fuelling and why?
3. What two main factors must be guarded against in handling spent fuels?
4. Give two affects that you feel might be undesirable if spent fuel is badly mishandled.

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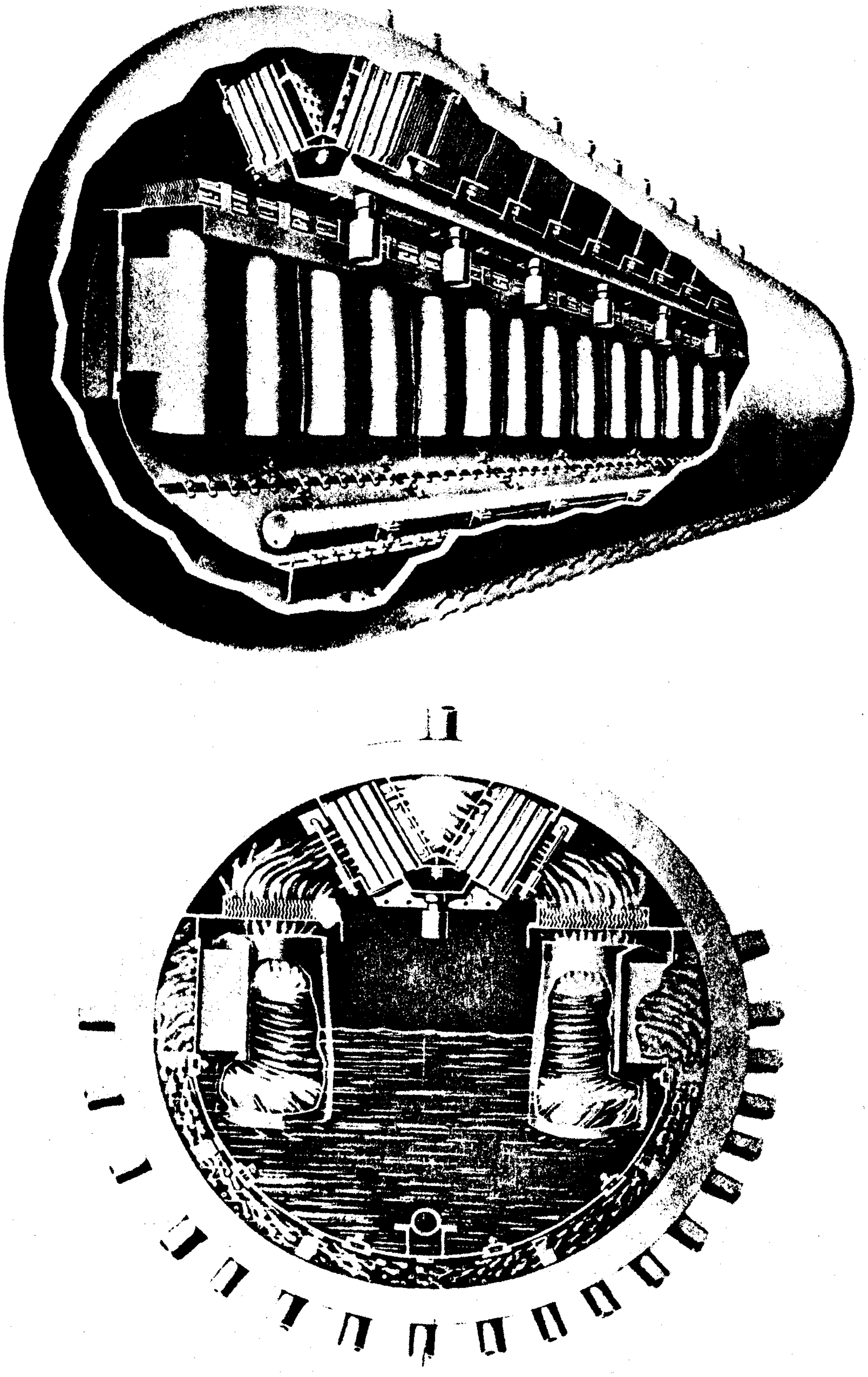
BOILER STEAM AND WATER SYSTEMS

It was noted in an earlier lesson, that the reactor is a source of heat, and serves the purpose of a "furnace" in a nuclear generating station. The use of a reactor results in some major changes in conventional steam production equipment, as well as the special equipment which is associated with the reactor itself. The "boiler" in a fossil fired station normally includes combustion equipment, a superheater, an economizer, an air heater, etc. Depending on the design of a nuclear station, some of this equipment may be used, but probably in a modified form. For example, serious consideration has been given to the use of fossil fired superheaters in a nuclear station to improve steam conditions, and hence increase efficiency. A type of economizer may also be used, and will be discussed later.

Some nuclear station designs involve a direct cycle where steam is produced in the coolant, as it passes through the reactor, and is then taken directly to the turbine. However, the common arrangement (and the one which will be considered in this lesson) is to use a heat transport system which carries heat from the reactor to the boiler. This heat converts light water into steam which is then used in a conventional turbine cycle. This arrangement prevents activity from getting to the turbine; so that no shielding is required in the conventional part of the station.

Heat Exchanger and Steam Drum

The hot heat transport fluid is circulated from the reactor to the heat exchanger, where it gives up its heat and then returns to the reactor. The heat is used to produce steam on the shell side of the heat exchanger. The steam formed is separated from the water in the steam drum, and then proceeds to the turbine as saturated steam. The heat exchanger is connected to the steam drum by risers and downcomers, which permit circulation of the boiler water. In low pressure units (below approximately 2500 psi) natural circulation is generally sufficient. The driving force is due to the difference in density between the steam bubble-water mixture in the riser and the cooler water in the downcomers.



Boiler Steam Drum

Fig. 1

If the pressure is above about 2500 psi, then the density of steam and water are so similar, that natural circulation is inadequate. In these cases, a pump is used to force circulation of the boiler water.

The steam must be adequately separated from the water in the steam drum, so that a minimum amount of water and impurities are carried with the steam to the turbine. This material in the steam would cause serious erosion of the turbine blades. For low steaming rates, there will be sufficient time for the steam bubbles to separate from the mixture by gravity without being drawn into the downcomers, and without carrying entrained water droplets into the steam outlet. However, for this same arrangement at a higher rate of steam generation, the time is insufficient to attain either of these desirable results. Most steam drums, therefore, are fitted with some form of mechanical separator. In a simple form, these separators might be only a set of baffles which force the wet steam to change direction. A more elaborate system may use centrifugal force as a primary separator (steam-water mixture is forced through a "cyclone" separator which swirls the mixture in small cylinders mounted in the steam drum) and scrubbers as a secondary separator. The scrubbers are simply a series of close fitting plates which force the steam to travel a tortuous path between them. The water and impurities in the steam collect on the plates, and drain off the bottom. The general arrangement of the separating equipment in one type of steam drum is shown in Figure 1.

In addition to the risers and downcomers, the following connections are likely to be found on the steam drum:

1. Steam line to turbine
2. Feedwater from the feedheating equipment
3. Pressure relief connection
4. Blowoff connection
5. Chemical feed connection
6. Instrument connections

Two possible arrangements of heat exchanger and steam drum are shown in Figures 2 and 3. The arrangement of Figure 2 is the one used in NPD , and Figure 3 is used at Douglas Point. In Figure 3, one leg of the vertical heat exchanger is used to heat the feedwater, and could perhaps be considered as a type of economizer.

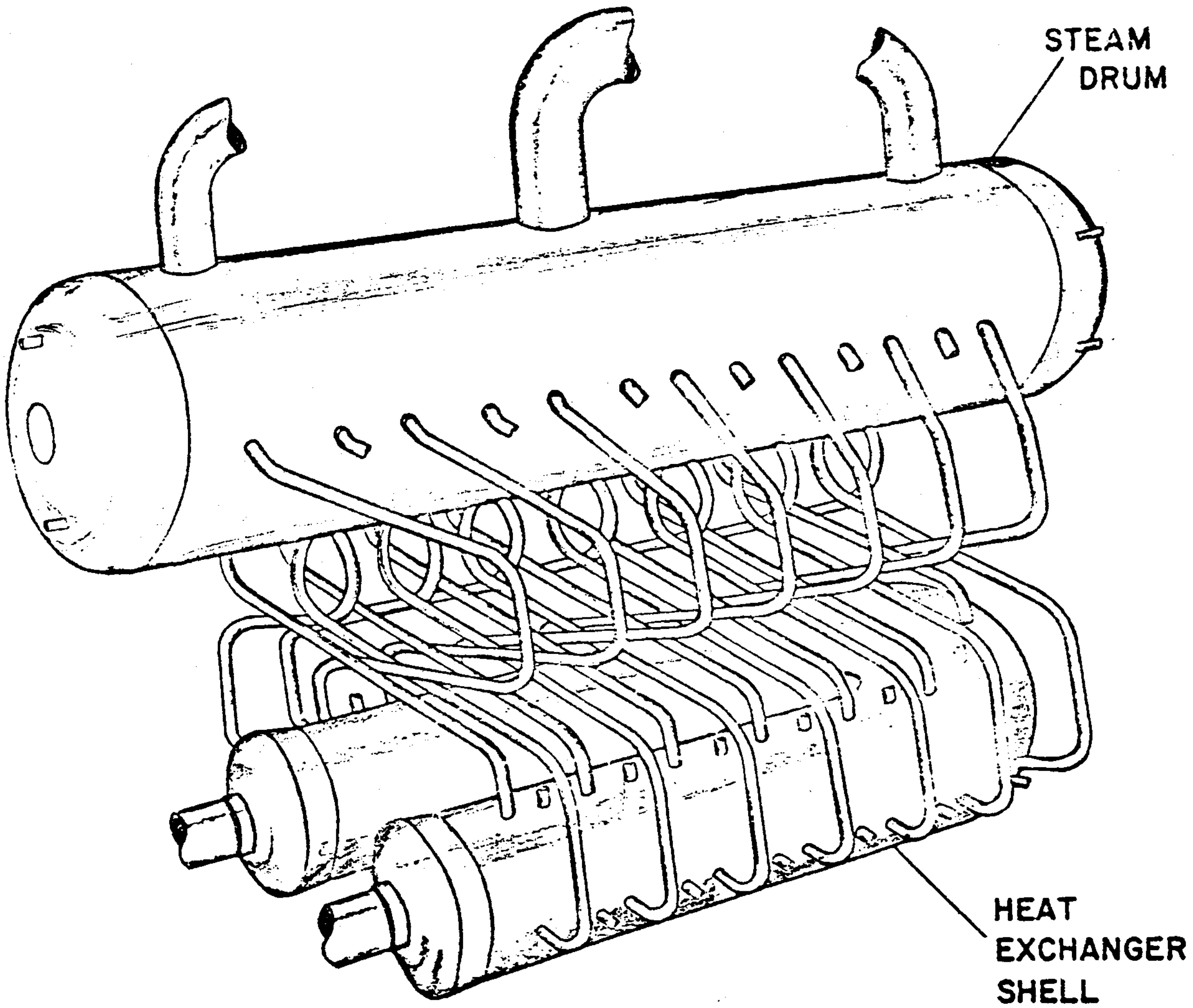

STEAM DRUM
HEAT EXCHANGER SHELL

Fig. 2

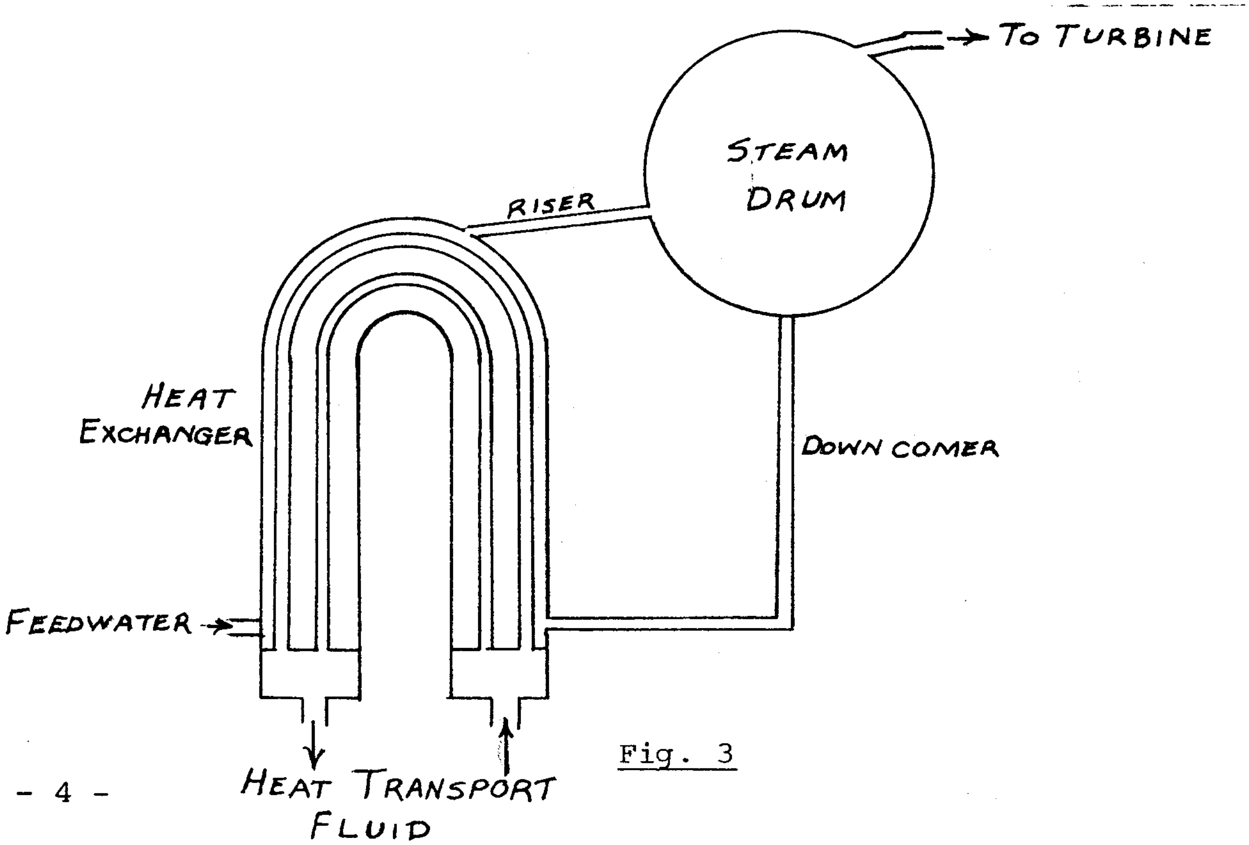

To TURBINE
STEAM DRUM
RISER
HEAT EXCHANGER
DOWN COMER
FEEDWATER
HEAT TRANSPORT FLUID

Fig. 3

Steam Relief and Blowdown

Any pressure vessel (a vessel which has a pressure higher than 15 psig) must conform to the ASME Boiler and Pressure Vessel Code. This code includes the requirements for safety valves, specifying the size, shape, number, location, type etc. The basic objective is to guarantee that the safety valves will discharge all the steam that can be generated without the pressure exceeding the valve settings by more than 6 per cent. This ruling is an example of many which must receive special interpretation in a nuclear plant. The limit "all the steam which can be generated" cannot be applied to the reactor since it is capable of generating heat at a rate far in excess of normal operation, but must be applied to the maximum steam raising capacity of the heat transport system or some other assumptions made.

The boiler will also be equipped with some method of blowdown. In normal operation, blowdown lowers the suspended solids and dissolved solids content of the boiler water. These solids are added by the feedwater, and since the steam leaving the boiler is relatively pure, concentration of solids will develop in the boiler water. Excessive amounts of suspended solids will cause deposition of sludge, and may alter the surface tension of the boiler water. This effect, in turn, may be severe enough to cause carryover of water with the steam in the absence of suitable anti-foam agents. Excessive amounts of dissolved solids have the same adverse effects as suspended solids and, in addition, when the solubility of salts present in the boiler is exceeded, scale will be deposited.

There are two principle types of blowdown - intermittent manual blowdown and continuous blowdown. Manual blowdown or sludge blowdown, is necessary for the operation of a boiler regardless as to whether or not continuous blowdown is also installed. The blowdown or blowoff connection is usually at the lowest part of a boiler (ie, the bottom of the heat exchanger) so that in addition to lowering the dissolved solids concentration of the boiler water, it will also remove a portion of the sludge which is generally more concentrated in the lower part of the boiler.

Another type of blowdown which may be encountered, uses a take-off line located slightly below the working water level for the purpose of skimming sediment, and oil from the surface of the water. This type of installation is generally referred to as surface blowdown equipment.

Chemical Feed Equipment

Chemicals are fed into the feedwater and boiler systems to control corrosion, and the concentration of undesirable salts. The boiler system is generally made of carbon steel which corrodes when the water contains significant quantities of dissolved gases such as carbon dioxide or oxygen. The carbon dioxide can be kept to a low concentration by maintaining a high pH and the oxygen can be removed with an oxygen scavenging material such as sodium sulphite or hydrazine.

The salts are removed by precipitating them in the boiler to form a sludge which is then removed by blowdown. This minimizes the formation of scale in the boiler. The precipitation is often accomplished by the addition of sodium phosphate.

The chemicals are generally added to the feedwater, and to the water in the steam drum as a solution. The equipment will normally include chemical mixing tanks and injection pumps. The injection pumps will be designed so that the amount of chemical solution added can be carefully controlled.

ASSIGNMENT

1. What is meant by and what causes natural circulation in a boiler?
2. Why are separators installed in a steam drum?
3. What is the purpose of boiler blowdown?
4. What are the two places in a boiler where you might find blowdown take-offs?
5. What is the purpose of putting chemicals in the boiler water?

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