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ROYAL NAVAL COLLEGE
GREENWICH

NAPC

REACTOR ACCIDENTS

DEPARTMENT
OF
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NAPC

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1. ACCIDENT DEFINITION AND ACCIDENT CATEGORIES

A reactor accident is defined as:

> "As an unexpected event involving a reactor which is likely to lead to or has resulted in a release of fission products external to the fuel".

Accidents are classified under three categories:

1.1 Category 1 Accident

An event which is likely to lead to or has resulted in a release of fission products from the fuel.

1.2 Category 2 Accident

An event which has led to a radiation hazard as the result of fission products released from the fuel.

1.3 Category 3 Accident

An event which has led to the release of fission products from the fuel to the environment outside the pressure hull.

1.4 Major Incident Definition

An abnormal occurrence (such as a serious fire) which poses a potential threat to, or causes serious concern for, reactor plant safety, but where reasonable grounds exist for concluding that a reactor accident is not likely to occur.

The likelihood of an accident is low; the plant is designed and assessed rigourously; it is constructed to meticulous standards, every weld in the high pressure systems is radiographed and tested in detail; operators are trained to a very high standard and all procedures are fully documented but yet - accidents do happen! However, it must be emphasised emphatically that there is not the remotest possibility of a violent explosion like an 'atomic bomb'; such explosions are so technically difficult to achieve, that it is not even considered as a remote possibility.

2. BARRIERS TO FISSION PRODUCT RELEASE

It is the highly beta-gamma active fission products which are the hazard in a reactor accident situation and it is their release to the environment which must be prevented by all means available. Under normal conditions, these fission products, which build up to exceedingly high levels during operation, are contained by four successive levels of barrier.

2.1 Fuel Clad

The zircalloy cladding of individual fuel elements is designed as the first level barrier to contain fission products. The plant is operated in such a way as to avoid a rupture of the clad with its consequent release of fission products.

2.2 Primary Circuit

The primary circuit, containing high pressure water, is the second level barrier. Ideally it should have no leaks, thus following a fuel element rupture fission products escaping into the primary circuit should be able to escape no further.

2.3 Primary Containment

The reactor compartment boundary formed by its forward and after bulkheads and the pressure hull between them is referred to as the Primary Containment and forms the third level boundary. It must always be intact whenever the plant is operating and is designed to withstand severe pressure surges.

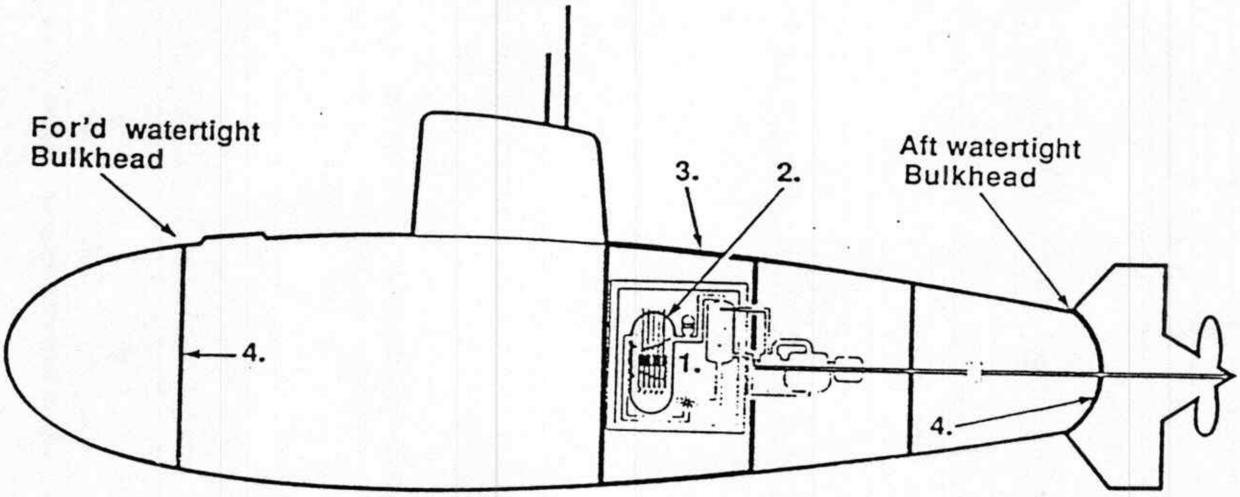
However the bulkheads are penetrated in a number of places (steam pipes, electrical supplies etc) and small leaks are likely. At start of life the compartment is pressure tested and the leak rate should not be more than 1% per day. This however may deteriorate with age.

2.4 Secondary Containment

This is an additional boundary outside the Primary Containment. It is formed by securing the bulkheads forward and after the reactor compartment. In the ultimate all access hatches to the submarine can be shut and the secondary containment boundary then becames the complete submarine pressure hull. Secondary containment is not an alternative to primary containment, it is complementary to it.

It is established by the crew immediately after an accident to prevent the further spread of any activity escaping from the reactor compartment.

For any submarine in a berth whose reactor is operating, secondary containment should be available within ten minutes.



1. Fuel Elements and Cladding
2. Primary Circuit Boundary (nil leakage)
3. Primary Containment Boundary
4. Secondary Containment Boundary

FIG 2.1 - BARRIERS TO FISSION PRODUCT RELEASE

3. CLASSES OF REACTOR ACCIDENT

An infinitely wide range of reactor accidents can be postulated, but for simplicity they can be grouped under three main headings depending on which barriers are breached.

3.1 Core Damage Accident

This involves the breaching of Barrier 1 (fuel clad) only, to a greater or lesser extent. It will result in the release of fission products into the primary circuit and may give rise to extremely high levels of radiation in and around the reactor compartment and around the submarine. Such an accident will pose major problems for Base and Ship's staff but since the fission products are safely contained within the primary circuit, there will be no hazard whatsoever outside the Base area, therefore in the context of accident organisation and procedures this class of accidnt is considered no further.

3.2 Loss of Coolant Accident

This class of accident involves a failure of Barrier 1 (fuel clad) and Barrier 2 (primary circuit boundary); the failure of the fuel clad being a consequence of a primary circuit boundary failure.

It will lead to the release of fission products into the reactor compartment and although this is strictly a contained release, it must be assumed as a matter of policy that because of the high pressures generated a small fraction will seep out of the reactor compartment over some 24 hours. The extent to which it may reach the environment will depend on how well secondary containment has been established.

In its worst case, this type of accident is expected to have a probability of 1 in 10,000 reactor operating years.

3.3 Containment Failure Accident

Failures in Barriers 1 (fuel clad), 2 (primary circuit) and 3 (primary containment) which, in the worst case could be a breach of the pressure hull, by-passing secondary containment thus releasing fission products directly to the environment.

Because this uncontained accident involves a third failure, it is much less probable than a coolant boundary failure but its consequences would be much more severe. It is estimated that this accident would result in the release of large quantities of mixed fission products to the environment over perhaps an hour. It has a maximum probability of 1 in 1 million reactor operating years.

4. BASIS FOR CONTINGENCY PLANNING

Having considered three classes of accident in the previous section, it is necessary to decide which should be used as the starting point for contingency planning. Since the Core Damage Accident produces no hazard outside the Base Area, it does not call for emergency procedures beyond its immediate vicinity. It might be suggested that planning should be based on the worst conceivable accident, ie a Containment Failure Accident but the International Commission on Radiation Protection Report No 40 on Accident Planning Principles recommends that no single accident sequence should be used as a basis for planning, rather a range of accidents, but the degree of detail within the plan should decrease as the probability of the accident decreases. For this reason, the consequences of the more probable Loss of Coolant accident are considered in greater detail. However it has to be borne in mind that worse accidents are possible, though improbable and contingency planning must be sufficiently flexible to allow for them.

5. DEVELOPMENT OF A REACTOR ACCIDENT

It is assumed that the reactor is operating at power when there is a catastophic break in one of the main, primary pipes at a point where it cannot be isolated. Moreover, the ends of the break separate so that there is no flow across it.

5.1 Sequence of Events

As a result of the primary circuit breach, there will be an instantaneous drop in primary pressure; water in the loop and in the reactor will flash off into steam and escape into the reactor compartment. Reactor compartment temperature and pressure will rise rapidly until within a few seconds compartment and circuit pressures equalise. It is estimated that this will be within the design capability of the reactor compartment. From then on, conduction of heat through the pressure hull will reduce temperature and pressure.

By this time, the reactor will have been shut down, but because of the disappearance of coolant, the large amounts of decay heat being generated in the core will raise fuel temperature rapidly. When fuel temperature reaches 900 C a chemical reaction takes place, the zirconium oxidising, taking oxygen from the surrounding steam and releasing large quantities of heat in the process.

As a result:

a. There is a second pressure surge.

b. The core temperature will rise more rapidly and at about 2000°C will melt releasing fission products to the reactor compartment.

c. There will be a build up of hydrogen.

The second pressure surge will again be within the design capability of the reactor compartment.

There may be a third pressure surge if the hydrogen/steam/air mixture forms in the correct proportions for it to explode.

If the rate of production exceeds the rate of heat loss to sea and air outside the hull, there could be a fourth smaller pressure peak within 1 to 3 hours.

From then on, fission products and steam will cool by conduction through the hull. Reactor compartment pressure is expected to have fallen to a little above atmospheric in 24 hours.

It is extremely important that the cooling be as rapid as possible since it is the high pressure inside which is pushing steam and fission products out through penetrations in the reactor compartment bulkhead.

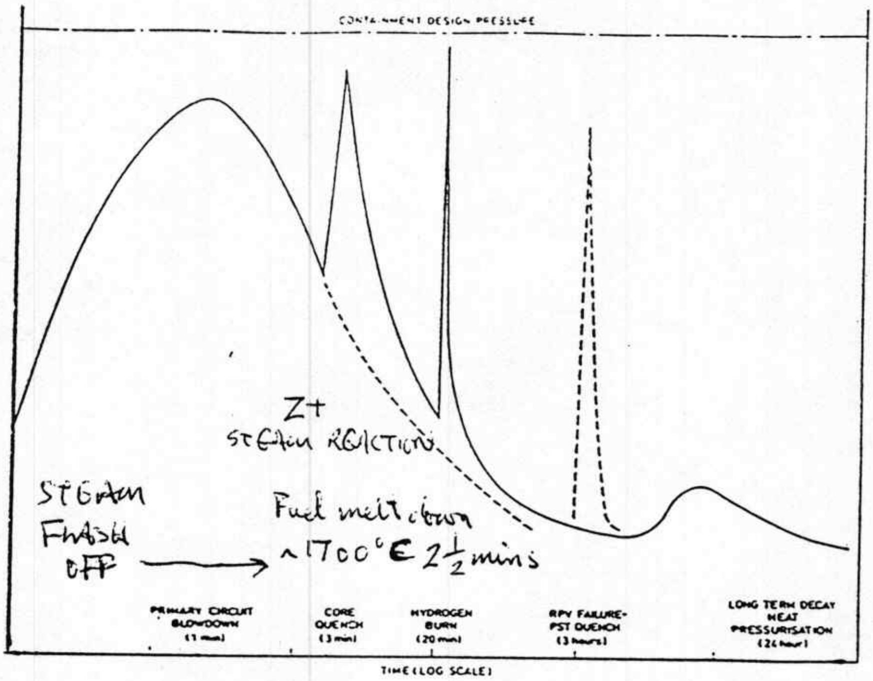


FIG 6.1 - PRESSURE SURGES FOLLOWING LOSS OF COOLANT ACCIDENTS

In the case of a reactor accident which results from a much less catastrophic loss of coolant water, the temperature rises more slowly. However, once the zirconium/steam reaction threshold temperature is reached, the same rapid sequence of events will be produced.

5.2 Isotopes Released into Reactor Compartment

It is the most volatile fission products which will be released into the reactor compartment. The most important of these will be:

Xenon
Krypton
Iodine
Caesium
Strontium
Ruthenium

Exactly how they will behave is extremely difficult to predict; much depends on their physical and chemical properties at these elevated temperatures and pressures. Some, particularly the more volatile materials will remain as vapours. Some will condense on cooler surfaces, some plate out, some form chemical combinatins and others disolve in the water at the bottom of the Compartment.

5.3 Quantity of Fission Products Released into the Reactor Compartment

The level of fission products in the reactor core depends upon:

a. Power - this determines the level of short lived fission product activity.

b. Core Age - this determines the level of long lived fission product activity.

For planning purposes, the following assumptions are made:

a. The plant is operating at its normal temperature and pressure at the time of the accident.

b. The core has a "Standard" history viz:

(1) it is at the end of its life

(2) the core has operated at 100% power for the last 100 hours

(3) for the rest of its life it operated continuously at 25% power.

Calculations show that under these conditions, the core will contain approximately 4×10^{18} Bq of mixed fission products of which, 1% or 4×10^{16} Bq is I131.

In a Loss of Coolant Accident, the fraction of fission products released from the fuel into the reactor compartment depends on their volatility. For some, 100% will be released, for others, only a small fraction.

The conditions assumed are pessimistic; a standard core history is unlikely to occur in practice. The figures quoted are therefore likely to be a pesimistic over estimation. life history 25%, old core, 100% for last 4 days before accident

6. FISSION PRODUCT ESCAPE TO THE ENVIRONMENT

The quantity of fission products reaching the environment will depend on the magnitude of the accident, the fractions of fission products released from the fuel and on the degree of containment.

If both primary and secondary containment are fully secured, then the activity escaping will be small, and likely to be in the region of 4×10^{12} - 4×10^{13} Bq of mixed fission products of which 4×10^{10} - 4×10^{11} Bq are I131. The release is likely over within 24 hours.

If however, containment is degraded ie either primary or secondary containment is breached, (but not both) then a release in the range 4×10^{14} - 4×10^{15} Bq (of which 4×10^{12} - 4×10^{13} Bq is I131) is likely over 24 hours.

Following a primary containment failure accident where the pressure hull is breached and secondary containment by-passed, then the consequence is a sudden release of $4 \times 10^{16} - 4 \times 10^{18}$ Bq of mixed fission products (including $4 \times 10^{14} - 4 \times 10^{16}$ Bq of I131) direct to the environment in less than an hour.