4. Accident Scenarios, Source Terms and Environmental Consequences

4.1 Source Term Concepts: Overview and Readers Guide to this Chapter

The Source Term is the release to the atmosphere of radioactive matter, like noble gases, iodine and cesium, that can occur as a result of an accident.

In this chapter the reader is assisted by explaining central concepts of source term technology, namely the fuel inventory of radioactivity, confinement barriers, leak paths and releases to the atmosphere, i.e. Source Terms.

The complete range of possible outcomes of an accident is mapped up by pointing out those plant, core and containment states that strongly affect releases to the atmosphere, Table 4.1.

The Source Terms can vary in size over at least seven orders of magnitude and are accordingly sorted into seven Classes of severity: from small foreseen Design Basis Accident (Class 1) through to extreme events (Class 7) on the International Nuclear Event Scale (INES) [8]. The INES scale is given in Appendix 3. This scale was originated for use in retrospect to record post factum the outcome of particular event and to communicate its severity via mass media to the general public. The outcome of the two well known historical accidents in 1979 at Three Mile Island (unit 2, Harrisburg) and in 1986 at Chernobyl (unit 4) is benchmarked.

A “rule of thumb” formalism is suggested for use in the emergency organization in order to provide as early as possible in an acute emergency a rough order of magnitude prediction of an imminent Source Term. This early prediction will later in time be modified and substantiated by real data from monitor observations when they eventually become available.

4.2 Introduction to Accident Scenarios and Source Terms

The fuel and the containment are the major entities in source term predictions. Their states are represented by s (release), e (emission) and L (leakage), respectively, in the prediction formalism:

$$s = e \cdot L\ ,$$

that is suggested for application in this Emergency Preparedness Handbook. This formalism will be explained in discussing below how accident scenarios affect source terms and environmental consequences. Table 4.1 provides the scenario map and organizing structure for this discussion. Confinement zones of Ignalina NPP are shown on Fig. 4.1.

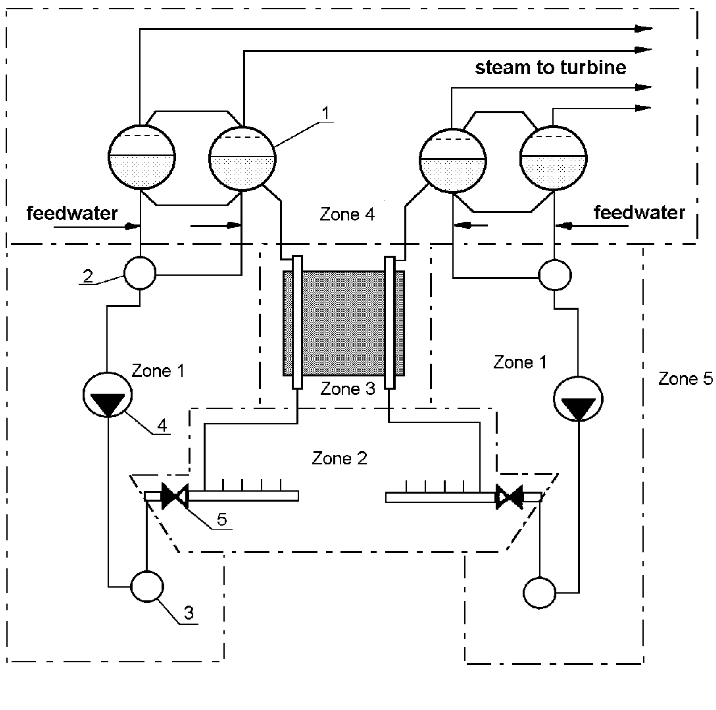

Fig. 4.1 Ignalina NPP confinement zones [9]:
1 - steam separator; 2 - suction header; 3 - pressure header; 4 - main circulation pump; 5 - check valve

Table 4.1 Scenario map. Overview of plant, core and confinement states with their corresponding source terms, adopted from [7]

INES	PLANT STATES		CORE STATES				CONTAINMENT STATES			SOURCE TERMS	REMARKS
	Accident Initiators	Failure of Support & Safety Functions	Fuel States	Pressure Tube States	Hydrogen States	Graphite Stack States	Zone 3 States	Zone 4 States	ACS States	As Now Operated	
0			S = Safe stable cooling			Operating temperature	Inerted, unburnable	Inerted, unburnable	Inerted, unburnable	s = e·L	
1 2 3	LOCAs Transients	Available apart from single failures	V = Violation of heat remove from fuel at preserved geometry	Small local damage	Small amounts	Heated locally				$e = 10^{-5} \rightarrow 10^{-3}$ L = 0.01 $s = 10^{-7} \rightarrow 10^{-5}$	Inside Design Basis
4	Local flow blockages Station blackout	Temporary	D = Damage to fuel by local melting	Multiple pressure tube rupture at low pressure	Medium amounts	Graphite stack cooled via control rod coolant flow	Fuel channel top end heat up to failure into Zone 4	Structure of Zone 4 remain sound	Molten fuel opens vent path via Zone 3 to Zone 2	e = 0.002 L = 0.1 s = 0.0002	Somewhat beyond Design Basis
5	Station blackout	Longer	A = Severe Accident Global melting		Large H_2 evolution from fuel and pressure tubes	Control rod channel boil dry and graphite heat up	Low end fuel meltout into ACS			$e = 0.1 \rightarrow 0.5$ $L = 0.1 \rightarrow 0.2$ s = 0.01	Clearly beyond Design Basis
6	Station blackout	Prolonged		Multiple pressure tube rupture at high pressure		Air ingress to hot graphite causes fire	Upper core plate uprise into Zone 4 Low end fuel meltout into ACS	Zone 4 structure failed by press beyond relief Transport of $FP+H_2+$ steam via Zone 4 to atmosphere	Hot gases from Molten fuel open vent path from Zone 3 to Zone 4	$e = 0.5 \rightarrow 0.8$ $L = 0.2 \rightarrow 1$ s = 0.1	Severe Accident far beyond Design Basis
7			RIA induced power transient, e.g. Chernobyl	Damaged	Large amounts	H_2 and graphite fires	Open upwards to Zone 4	Open to the atmosphere		$e = 0.8 \rightarrow 1.0$ $L = 0.5 \rightarrow 1$ $s = 0.5 \rightarrow 1$	Extreme event

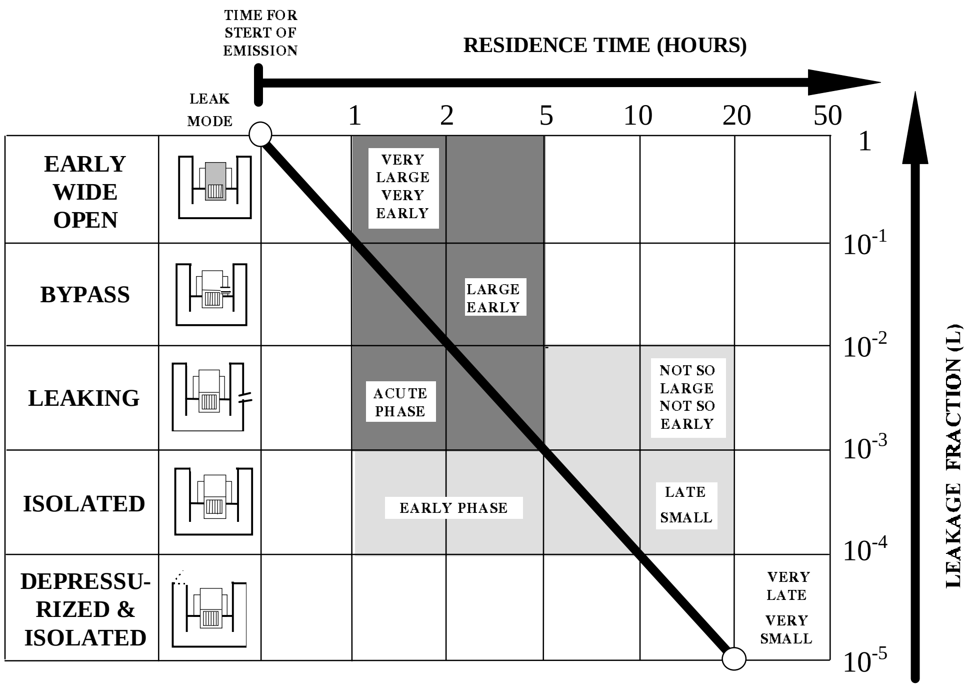

Fig. 4.2 Release prediction

4.3 Source Terms

4.3.1 Rule of thumb

Early in an emergency there is a need for a quick rough release predictions in support of planning of the emergency response. The rule of thumb provides a tool to assess releases to the atmosphere.

The rules of thumb focus on three major items:

- the emission from fuel of noble gases, iodine and cesium;
- the containment barrier and its leak path to the atmosphere;
- the removal processes in transport of radio-activity from fuel to atmosphere.

The form and contents of the thumb rules and their basis are discussed below.

4.3.2 The Formalism s = e·L

The formalism is intended to provide the emergency staff with a tool for answering early in an accident the pertinent questions:

Will there be a release ?
How large can it be?
When can it occur?
How long can it last ?

“Will there be a release ?” The fuel and containment are recognized as the main barriers that prevent release of radioactivity to the atmosphere. As long as the fuel is intact and the containment is leak tight, no significant release will occur.

"How large can the release be ?" The rule of thumb answer is: “**S/I** = s = e·L”, where “**S**” is the release to the atmosphere expressed as a fraction of inventory “**I**”. The rule of thumb enables the emergency staff to early focus their attention on the three main factors that constitute the accident's release potential, that is: **I**, e and L.

S and **I** are quantities of radioactivity in Becquerel. They are here written in bold type. s, e and L are dimensionless fractions of inventory **I (** Figure 4.2).

The fuel core holds volatile noble gases, iodine and cesium. This is the inventory “**I**”. The Data Handbook provides plant specific amounts in Becquerel. In the course of the accident, the fuel can become heated and emit a fraction “e” from the fuel of its contents of noble gases, iodine, cesium in gasborne form to the containment. The emission “e” of gasborne noble gases, iodine, and cesium will increase with fuel temperature. The fuel temperature and extent of fuel damage will increase with the uncovery time, that is the time interval during which the fuel by accident stays in lack of water for cooling. Given a leak path, a fraction “L” of the emitted gasbome amount of iodine and cesium will leak from the containment to the atmosphere. For noble gases “L = l” as they sooner or later will escape. For iodine and cesium L will be smaller, less than 1.

Also for iodine and cesium there is a general tendency borne out by source term studies. Figure 4.2, that:

- Leak modes with short residence times have large leak fractions;
- Leak modes with long residence times have small leak fractions.

4.4 Accident Scenarios

4.4.1 Sequences and scenarios

When specific events in a specific plant are discussed, specific accident sequence*s* are defined. A collection of accident sequences can have some features in common for instance, type of plant, type of accident initiator, type of containment structure. Such collections of sequences are referred to as accident scenarios. Because of similarities between scenarios, they are useful in this Handbook, for e.g. source term predictions. Some scenario features strongly affect the source term. In Table 4.1 are mapped out those scenario features at Ignalina NPP that most strongly affect source terms and consequently should be recognized when planning source term studies or making source term predictions.

4.4.2 Scenario map

The scenario map, Table 4.1, recognizes the plant states, core states and containment states as main features which are further divided into sub-features according to the table. The severity of an accident can in retrospect be compared with the INES scale [8] which recognizes seven classes of accidents from the mildest to the most severe ones. The INES scale is suggested to be used here in this Handbook also as a prognostic tool to differentiate scenarios according to the size of their release potential.

4.5 Plant and Core States

4.5.1 Plant States and Core States

The Plant States in two columns recognize the accident initiators and the availability of support and safety functions. The Core States comprise four columns. The fuel states progress in the order S = Safe stable cooling, V = Violation, D = Damage, A = severe Accident from lesser to larger emission fractions (e) of volatile noble gases, iodine, cesium from the fuel. The largest emission fractions in class seven can be caused by reactivity induced accidents (RIA), like the one that occurred at Chernobyl in 1986. In that accident s = e L was larger than 0.5 for iodine and 0.3 for cesium, according to the recent review [10]. The pressure tube states progress from small local damage via single tube rupture to multiple pressure tube rupture at low as well as high pressure. The significance of this column is of course that it recognizes the potential for upper core plate upraise and lift off into zone 4 as occurred at Chernobyl. Some large LOCA accident initiators by themselves eliminate lid lift by relieving primary system pressure. The hydrogen states are important because a burn or explosion of large amounts of evolved hydrogen can damage or fail containment structures. The graphite stack states can progress from locally heated spots, via overall stack heat-up to air ingress and large scale fire, which will damage the fuel and emit its radioactive inventory.

4.5.2 Containment States

Zone 3 states comprise the core cavity compartment. As long as this compartment remains intact, source terms can be expected to remain small. Fuel melting in the channel can be expected to flow down and melt out into the ACS compartments. Pressurization of zone 3 by multiple tube failure at high pressure causes upper plate rise up into zone 4. Simultaneous upper and lower end failures of fuel channels open a path for natural circulation through the core of hot gases including hydrogen evolved from zirconium oxidation caused by steam and air ingress. Such a scenario transports a substantial part of the part of radioactive inventory emitted in fuel-air oxidation into zone 4.

Zone 4 states are mainly that the structures may remain sound throughout the sequence, and thereby mitigate releases by directing them via filters and the stack to the atmosphere. Alternatively**,** the zone 4 structures can be failed by steam and/or hydrogen-burn pressurization beyond relief capabilities, in which case most of the zone 4 gasborne radioactive content is released to the atmosphere.

The ACS sturdy structures can be expected to remain sound and confine radioactivity in most scenarios. Concern is with the above state of natural circulation of gases via the core to the atmosphere. There is also a concern for basement meltthrough as was imminent at Chernobyl.

4.5.3 Source Term Data and Formalism

Source Term escalation on the INES scale in classes 1 through 7 is exemplified in the last column according to the formalism $s = e \cdot L$**,** at present, for illustrative purpose only. Reliable quantitative source term data must be calculated on specific Ignalina NPP accident sequences using the available source term technology.

4.5.4 Three Mile Island and Chernobyl

At Three Mile Island severe damage, melting, to large fraction of the core caused emission from the fuel into the containment of large amounts of radioactivity,

$e = 0.5 \rightarrow 1$.

However the containment structure remained essentially leaktight throughout the accident and release to the atmosphere remained small,

$L = 10^{-3}$.

Then according to the rule of thumb:

$s = 1.0x1 = 1$	for noble gases and
$s = 0.5x10^{-3} = 0.0005$	for iodine and cesium.

Real releases at the Three Mile Island were:

$s = 0.05$	for noble gases,
$s = 0.5x10^{-7}$	for iodine, and
$s = 0$	for cesium.

This illustrates the point made below (see 4.6), that thumbrule estimates represent an upper bound.

At Chernobyl the violent Reactivity Induced Accident damaged at the same time the fuel and the confinement structures and caused release of a large fraction of the core radioactivity directly to the atmosphere. Real releases at the Chernobyl were:

$s = 1.0$	for noble gases,
$s = 0.5$	for iodine, and
$s = 0.3$	for cesium.

4.6 Uncertainties

Inherent to all source term predictions are large uncertainties, that amount to at least one, often several orders of magnitude. This holds true for source terms computed by modern mechanistic models and for thumb rule predictions, in particular. The above thumb rules are chosen to represent the upper (95th-percentile) bound of the uncertainty interval. Real releases can be expected to turn out lower than what is predicted by the rule of thumb.

4.7 Restrictions

The above discussion applies to the atmospheric source term, which means release to the atmosphere. The thumb rule formalism applies to near-term releases of gasborne radioactivity in the first hours up to first day of an accidental event, until monitor data become available as discussed above.

Spills to the ground of radioactive liquids, the aquatic source term, is not further treated here. Consequences of liquid releases are in the short term local.

4.8 Dose Calculations: Environmental Consequences

The source term provides input data for dose calculations by hand or by use of computer models like e.g. LENA. The results inform on doses incurred or avoided in specific areas by application of emergency protective measures like iodine tablets, sheltering, evacuation.

Consideration in the case of Ignalina NPP on the applicability and effectiveness of various counter-measures and estimations of final consequences are reflected in the following Chapters 5 and 6 of this Handbook.

4.9 Summary

The thumb rules can as illustrated help answer the questions:

> Will there be a release ?
> How large can it be ?
> When can it occur ?

The question finally:

> How long will the release last ?

will in practice be answered by the operators actions to cool the core and its debris by water filling and spraying inside the accident confinement system and by closing valves in the leak paths.