

Cut Sets

Reference Workbook

A “**cut set**” is a set of basic events (like component failures) that, when they occur, cause an undesirable event (like system failure) to occur.

Most reliability engineering decisions don’t involve “**cut sets**.” However, “**cut sets**” can help a small number of critical decisions. *Cut sets* are referenced throughout the reliability engineering industry, within standards, and by regulatory bodies. They can help identify “single points of failure” in a system and can be used to analyze complex systems.

Minimal Cut Sets

The nuclear power plant secondary cooling loop that has previously been examined is illustrated in Figure 16.1.

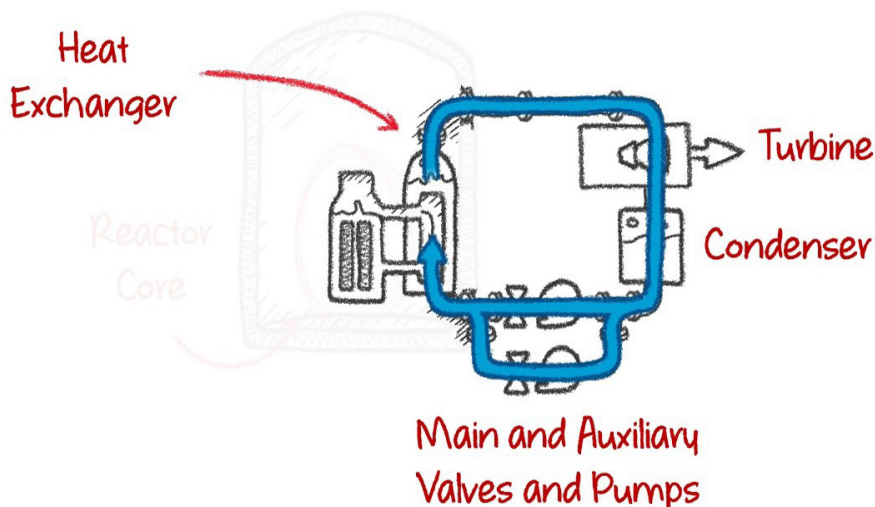


Figure 16.1: Nuclear power plant secondary cooling loop (water flow illustrated)

The heat generated in the core transfers through the heat exchanger to the water that makes up the secondary cooling loop. The water vaporizes to high-pressure steam that drives a turbine to generate electricity. The steam then enters the condenser, where it cools and condenses back into liquid water pumped through a main and auxiliary valve-and-pump subsystem back into the heat exchanger, and the cycle starts again. The Fault Tree that models the secondary cooling loop's reliability is illustrated in Figure 16.2.

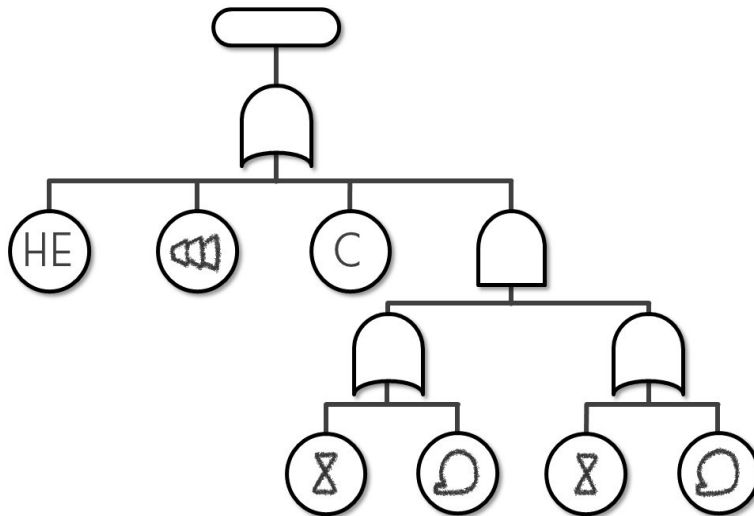


Figure 16.2: Secondary cooling loop reliability Fault Tree

It should be apparent that the secondary cooling loop (or any other system) fails if all components fail.

Because a **“cut set”** is a set of basic events (like component failures) which, when they occur, cause an undesirable event (like system failure) to occur, **the failures of all components in a system is a “cut set.”**

A cut set containing the failure events of all system components isn't insightful. It doesn't provide meaningful information as it is not a **“minimal cut set.”**

A **“minimal cut set”** is a (usually) smaller set of basic events (like component failures) that, only when they all occur, cause an undesirable event (like system failure) to occur.

“Minimal cut sets” help us understand how a system can fail. The secondary cooling loop has several **“minimal cut sets,”** including the pump on one pipeline and the valve on the other. The failure of these two components causes the secondary cooling loop to fail, as illustrated in the Fault Tree in Figure 16.3.

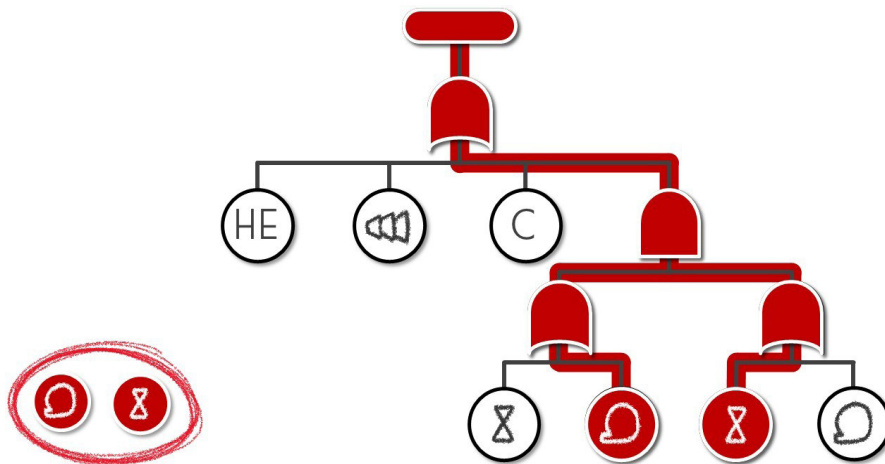


Figure 16.3: Secondary cooling loop reliability Fault Tree (illustrating a “minimal cut set” where failure is caused by the pump on one pipeline and the valve on the other)

One characteristic of a “minimal cut set” is that the system works if you ‘take away’ one component’s failure. For example, the secondary cooling loop would work if the valve in the “minimal cut set” illustrated in Figure 16.3 didn’t fail.

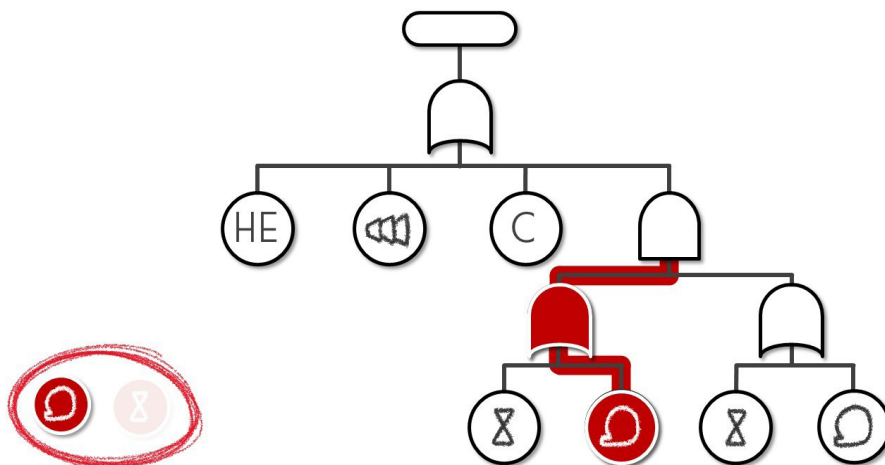


Figure 16.4: Secondary cooling loop reliability Fault Tree (illustrating how removing one failure event from a “minimal cut set” results in the system working or not failing)

All basic events (like component failures) in a **“minimal cut set”** need to occur for the undesirable event (like system failure) to occur. **“Minimal cut sets”** that involve more than one component (like the pump-valve pair on different pipelines) represent redundancy. The nature (size and number) of **“minimal cut sets”** can help us understand how our system fails.

Minimal Cut Set Analysis Using Fault Trees

The secondary cooling loop has several “*minimal cut sets*” that can be identified and used for decision-making. Finding them starts with “**indexing**” all basic events and logic gates.

Fault Tree indexing involves assigning (or visually placing) an *index* or *number* next to every *logic gate* and *basic event*.

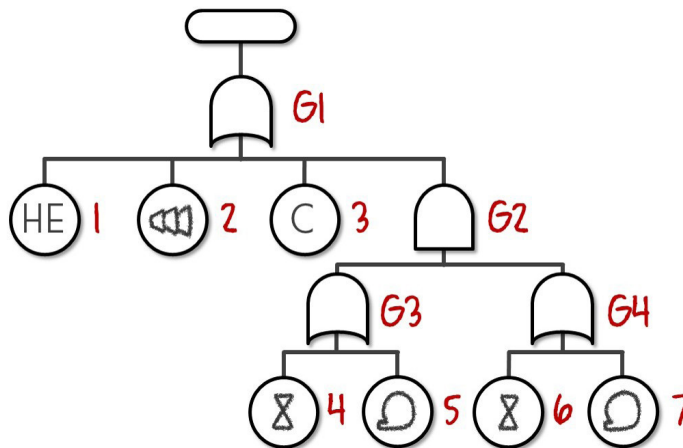


Figure 16.5: Indexed secondary cooling loop reliability Fault Tree

By convention, *logic gate* indices start with the letter ‘G.’ This helps indicate that they are not basic events (remembering “*minimal cut sets*” only contain basic events). Once indexed, we start working from the top down to find our *minimal cut sets*.

There are two rules for finding *minimal cut sets*.

Minimal Cut Set Rule 1: ‘OR’ gates increase the **number** of minimal cut sets. This is because ‘OR’ gates model series systems that increase the number of ways your system can fail.

Minimal Cut Set Rule 2: ‘AND’ gates increase the **size** of each minimal cut set, which is the number of basic events it contains. This is because ‘AND’ gates model parallel systems that increase how your system works (requiring more components to fail for your system to fail.)

Moving from the top down means first encountering the **'OR' gate** indexed 'G1.' If this **'OR' gate** is true, the system fails. From this perspective, **'OR' gate** G1 is a *"minimal cut set."* However, *"minimal cut sets"* can only contain *basic events* and not *logic gates*. **'OR' gate** G1 is now added to our list of *"minimal cut sets"* as a placeholder to facilitate further analysis.

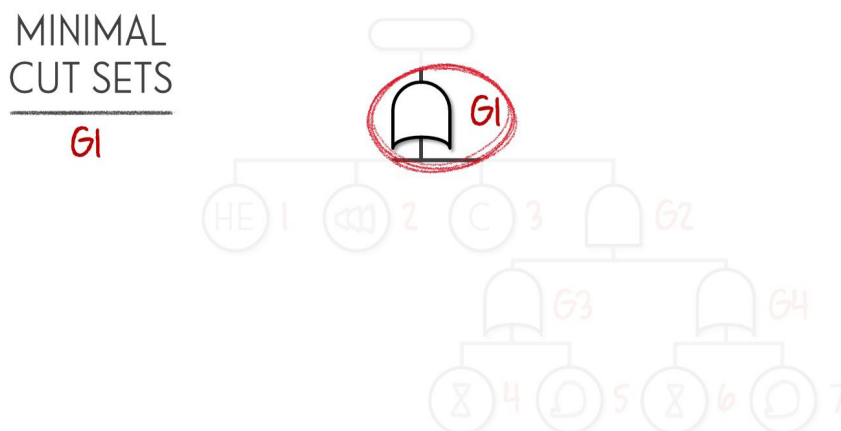


Figure 16.6: 'OR' gate G1 of the secondary cooling loop reliability Fault Tree

The next step is to analyze **'OR' gate** G1 further. It has four input events comprising three basic events indexed 1, 2, and 3, and the **'AND' gate** G2. A fault can propagate through an **'OR' gate** if any of its input events occur. This illustrates the first *minimal cut set* rule (**'OR' gates** increase the number of cut sets.) We can replace **'OR' gate** G1 in our *"minimal cut set"* list with all its input events.

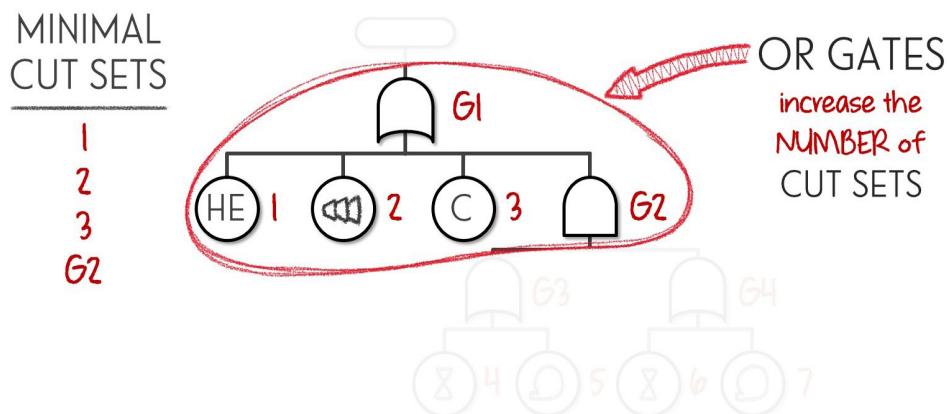


Figure 16.7: Minimal cut set list of the secondary cooling loop reliability Fault Tree (having analyzed 'OR' gate G1)

We have now identified three secondary cooling loop *"minimal cut sets."* Basic events 1, 2, and 3 correspond with the failure of the heat exchanger, turbine, and condenser. Figure 16.6 shows that three *"minimal cut sets"* are based on the failures of these three components. For example, the failure of the heat exchanger is a secondary cooling loop *"minimal cut set."* The same applies to the failures of the turbine and condenser. The three *"minimal cut sets,"* each containing a single basic event, are *"single points of failure."*

A **"single point of failure"** is a component within a system that, if it fails, would cause the entire system to fail.

"Single points of failure" indicate a lack of redundancy or backup options within the system for that area or component. Most systems have **"single points of failure."** However, safety or critical systems are often mandated to include redundancy at all levels. Finding a *"minimal cut set"* containing one basic event identifies an area of a safety or critical system that could be redesigned to incorporate redundancy.

The *"minimal cut set"* list in Figure 16.7 is still incomplete as it contains **'AND' gate G2**, which needs further analysis. **'AND' gate G2** has two input events, **'OR' gates G3 and G4**. We can then replace 'G2' in the list with 'G3' and 'G4' based on the second rule of *minimal cut sets* (**'AND' gates** increase the size of *minimal cut sets*).

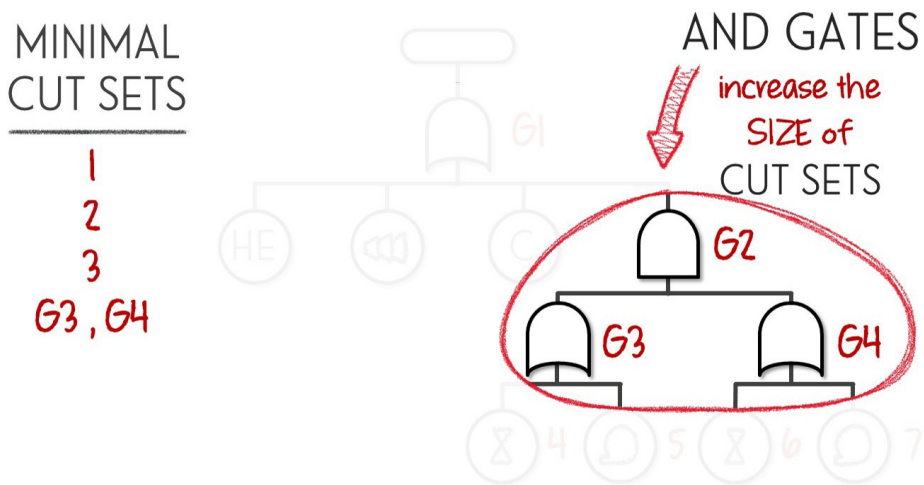


Figure 16.8: Minimal cut set list of the secondary cooling loop reliability Fault Tree (having analyzed 'AND' gate G2)

For the **'AND' gate G2** to cause system failure, both **'OR' gates G3 and G4** must be "true." So both **'OR' gates G3 and G4** appear in a single placeholder *"minimal cut set."* We keep analyzing our *"minimal cut set"* list, which still contains **'OR' gates G3 and G4**.

Focusing first on **'OR' gate G3**, we see it has two input (basic) events 4 and 5. From the first *minimal cut set rule* (**'OR' gates** increase the number of cut sets), we need to replicate the placeholder *"minimal cut set"* containing **'OR' gates G3 and G4**, replacing G3 in each one.

MINIMAL CUT SETS

1
2
3
4, G4
5, G4

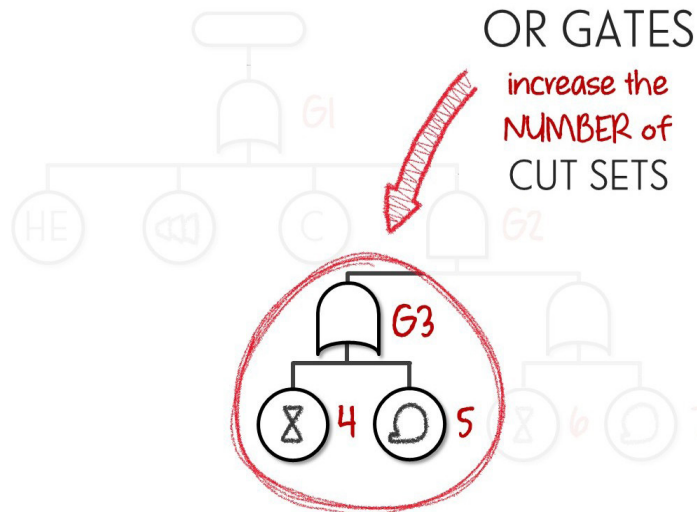


Figure 16.9: Minimal cut set list of the secondary cooling loop reliability Fault Tree (having analyzed 'OR' gate G3)

You can see how we now have two placeholder "minimal cut sets" in the list in Figure 16.9 as 'OR' gates increase the number of "minimal cut sets." We must continue analyzing the 'OR' gate G4 as it is still on the temporary "minimal cut set" list.

MINIMAL CUT SETS

1
2
3
4, 6
4, 7
5, 6
5, 7

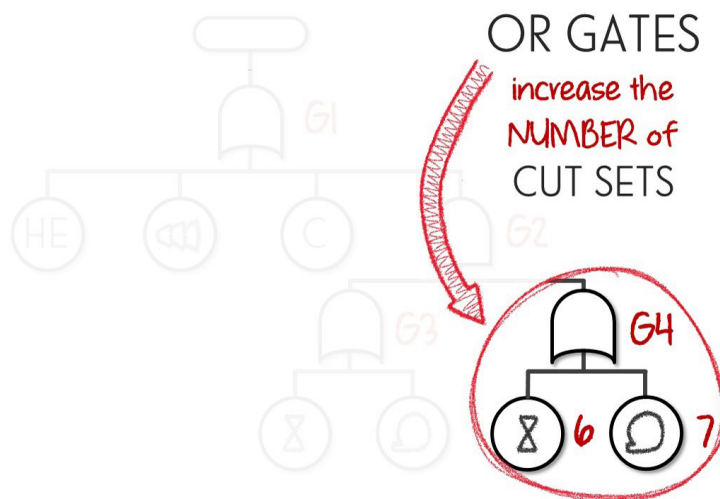


Figure 16.10: Minimal cut set list of the secondary cooling loop reliability Fault Tree (having analyzed 'OR' gate G4)

Analyzing 'OR' gate G4 meant adding another two "minimal cut sets" to the list above, as G4 appeared twice. We have now completed the "minimal cut set" analysis, as the "minimal cut set" list contains sets with basic events only.

Indices	basic event sets	
1	{HE}	single points of FAILURE
3	{C}	
4	{C}	
4, 6	{ Δ_1, Δ_2 }	
4, 7	{ Δ_1, Δ_2 }	
5, 6	{ Δ_1, Δ_2 }	
5, 7	{ Δ_1, Δ_2 }	

Table 16.1: Secondary cooling loop “minimal cut sets”.

Three of the seven “minimal cut sets” in Table 16.1 represent “single points of failure.” In other words, the secondary cooling loop will fail if any components in these “minimal cut sets” fail.

Minimal Cut Set Analysis Using Reliability Block Diagrams (RBDs)

Finding “minimal cut sets” from Fault Trees can be complex as a Fault Tree is a logic diagram. It can be easier to use the success paths of a *reliability block diagram (RBD)* to find “minimal cut sets.” The RBD that models secondary cooling loop reliability is illustrated in Figure 16.11.

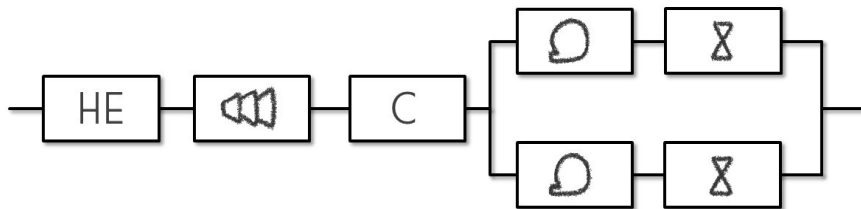


Figure 16.11: Reliability block diagram (RBD) that models secondary cooling loop reliability

This RBD contains two *success paths* or *tie sets* that show combinations of components that need to work for the system to work.

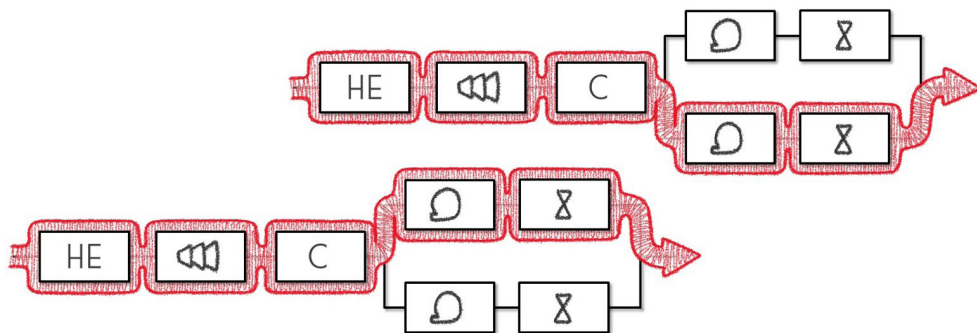


Figure 16.12: Success paths of the reliability block diagram (RBD) that models secondary cooling loop reliability

“Minimal cut sets” can be found by drawing lines through the blocks in the diagram in a way that “cuts” all success paths, like the one through the heat exchanger block in Figure 16.13.

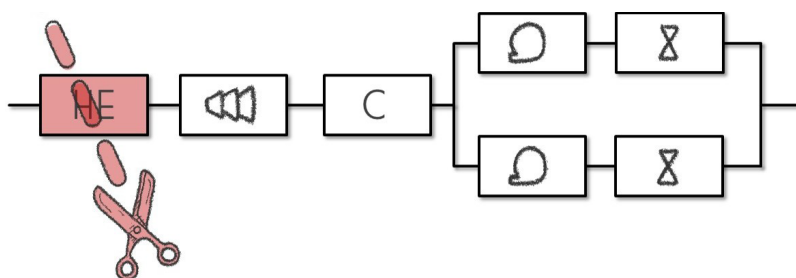


Figure 16.13: Example “minimal cut set” illustrated with the reliability block diagram (RBD) that models secondary cooling loop reliability

The cut in Figure 16.13 creates a *minimal cut set* because we can’t make it go through fewer blocks to stop all success paths. RBDs can make it easier to see and find all *minimal cut sets*, as illustrated in Figure 16.14.

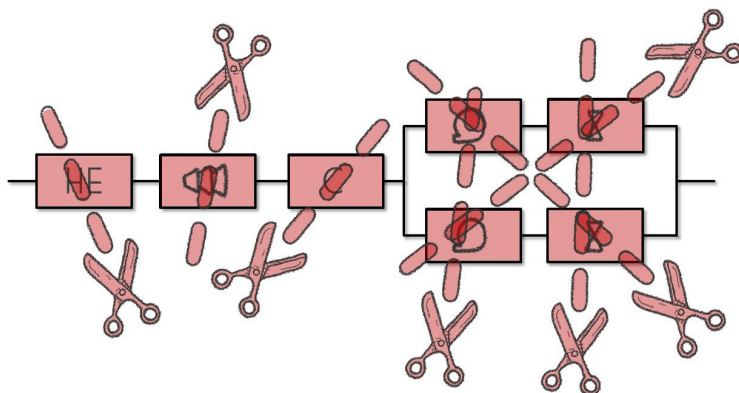


Figure 16.14: All seven “minimal cut sets” illustrated with the reliability block diagram (RBD) that models secondary cooling loop reliability

Minimal cut sets can be used for qualitative analysis that assesses system reliability without using numbers or probabilities. This includes finding single points of failure to identify where redundancy could be added to a design. The International Space Station has more than 3 million *minimal cut sets*. Engineers can be assigned more efficiently by focusing on the most vulnerable components and subsystems in smaller “*minimal cut sets*.”

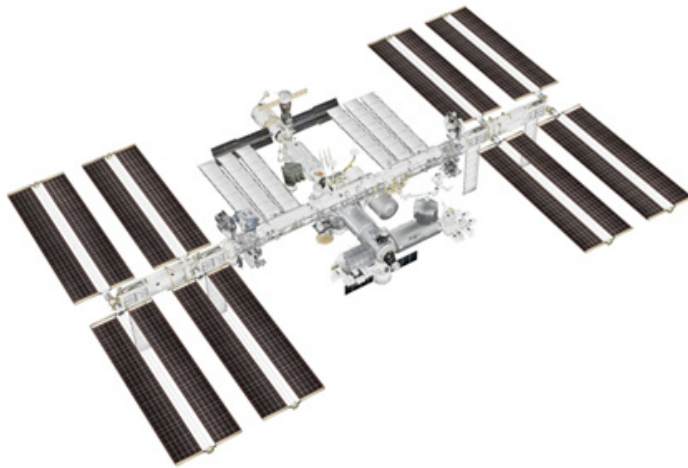


Figure 16.15: International Space Station (Image credit NASA)

Some software packages include algorithms that quickly find system *minimal cut sets* to calculate the probability of any of these “*minimal cut sets*” occurring to estimate system reliability. This can make complex system reliability analysis more straightforward for software programs. *Minimal cut sets* can be time-consuming to analyze manually, so software is often used for these applications.

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