Development of the endurance test program and the assembly fixture for TRITON11™

William Lundström

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William Lundström

LUND UNIVERSITY

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Abstract

The engineers at Westinghouse Electric Company have developed a new nuclear fuel design called TRITON11™, which will be used in Boiling Water Reactors (BWR). This project has been to develop a test program and an assembly fixture for TRITON11™.

The test program can not be fully presented in this repport due to confidentiality.

The test program is for the first scoping test that will be performed on the fuel to test the mechanical performance. The test program should test the limits of the structure but must still be reasonable and reflect the reality. The test will be performed under two-phase flow conditions to test the upper parts of the structure. This means that the temperature should be held constant at 280°C with a pressure of 70 bar and with a flow of 19 kg/s. The duration of the test should be at least 700 hours.

The test fuel rods that are used are longer than the Nordic and shorter than the Continental. Some of the components are therfore modified in length to adjust for this. These modifications should not affect the results substantially.

The assembly fixture is supposed to be used at the fuel laboratory where the tests will be performed. The fixture needs to hold the spacers firmly during the assembly of the fuel bundle. The position of the different spacer levels should be able to be adjusted in height.

The fixture is built up by four aluminum profiles that builds the corners. The corners are connected by a number of brackets at different positions. The spacers are placed inside a spacer holder that is placed on a level adjustment frame. The level adjustment frames and the brackets are connected to the corners by screws and nuts. The screw joint allows for an easy adjustment of the spacer levels. The bottom plate is held in place by a holder made in POM that is placed on top of a level adjustmend frame.

Both the Nordic and the Continental design can be assembled in the fixture. A holder for the transition piece needs to be used for the Conntinental design.

Keywords: Nuclear fuel, Boiling Water Reactor, fretting wear, test program, assembly fixture

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Lund, June 2016

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1 Introduction

A brief introduction to the company and the problem to be solved are presented in the following chapters.

1.1 Westinghouse

Westinghouse Electric Company is a world leading supplier of equipment for the nuclear industry and provides everything from fuel pellets to fully operational nuclear plants. The company was founded back in 1886 by the engineer George Westinghouse who developed an alternating-current system. The invention was successful and the company grew rapidly. By the year 1957 the first commercial pressurized water reactor (PWR) was released and today approximately one half of the world's nuclear reactors are built with the technology developed by Westinghouse (Westinghouse Electric Company).

By the year 2012 was approximately 11% of the world's electricity produced by nuclear power plants (Nuclear Energy Institute). As the world's population is growing the demand for energy grows and it is expected that the need for electricity will be nearly doubled by the year 2030. To be able to meet this demand and to stay as a competitive company on the market, it is important to deliver clean, safe and reliable energy (Westinghouse Electric Company).

Westinghouse Electric Sweden AB (Westinghouse in the future) is located in Västerås and Täby, with the head office, fuel factory and fuel laboratory located in Västerås. This is also where the development of the Boiling Water Reactors (BWR) for the Westinghouse group is performed. The non-destructive testing facility WesDyne is located in Täby.

1.2 Problem formulation

Westinghouse is currently working with the development of a new nuclear fuel for the BWR, called TRITON11™. Since safety is a major concern when developing nuclear equipment the project has come to a stage where the fuels endurance against fretting needs to be tested and verified.

Earlier designs allowed the developers to run a number of different tests on four sub assembly grids in the same fuel assembly. The new design however is approximately four times as big as the previous one. Due to the cost and time of running the test loop it is not possible to do four different tests, thus the test program for the previous design cannot be directly reused.

The aim of this project is to develop a new test program for TRITON11™ to test as many critical aspects as possible in one test loop.

Furthermore the assembly rig that is used to assemble the fuel bundle needs to be redesigned to fit the new fuel design. The components needed to do so will be constructed and drawings will be created. After the part and assembly drawings have been created the components will be ordered and manufactured.

1.3 Dispossition

The dispossition of this report will be in the chronological order which started with a brief introduction of the company and the problem. This is followed by a literature study containing information needed to understand the basic principles and background to the problem and which methods that are used to solve them.

After the literature study the steps to solve the project will be presented. This is followed by a results and discussion part.

The test program and the produced drawings cannot be fully presented in this report due to confidentiality.

2 Literature study

A short introduction to the BWR is presented in this chapter followed by the basics needed to understand the phenomena of grid-to-rod fretting wear. The method used in the project is presented in the end of this chapter.

2.1 The Boiling Water Reactor

One of the most common types of nuclear reactors is the Boiling Water Reactor. The reactor core is filled with fuel rods, which are metal tubes usually made of a zirconium alloy. The tube is filled with pellets of enriched uranium, which contains a higher concentration of the isotope ^{235}U.

During operation the fuel is bombarded with neutrons, which causes the atomic nuclei to split. When the uranium nuclei are split it emits new neutrons and energy is released. If the emitted neutron hits another nucleus the process is repeated and a chain reaction can be achieved. This process is more commonly known as the fission process.

In the boiling water reactor process, Figure 1, water is circulated in to the reactor core. The large amount of energy released by the fission process causes the water to evaporate. The steam is then dried and water droplets are returned to the system. The dried steam is transported to a turbine that starts to rotate. The turbine is connected to a generator creating electricity. After the steam has passed the turbine it enters a condenser and condensates. It is then pumped back in to the reactor and reheated, thus creating a closed cycle (Vattenfall AB).

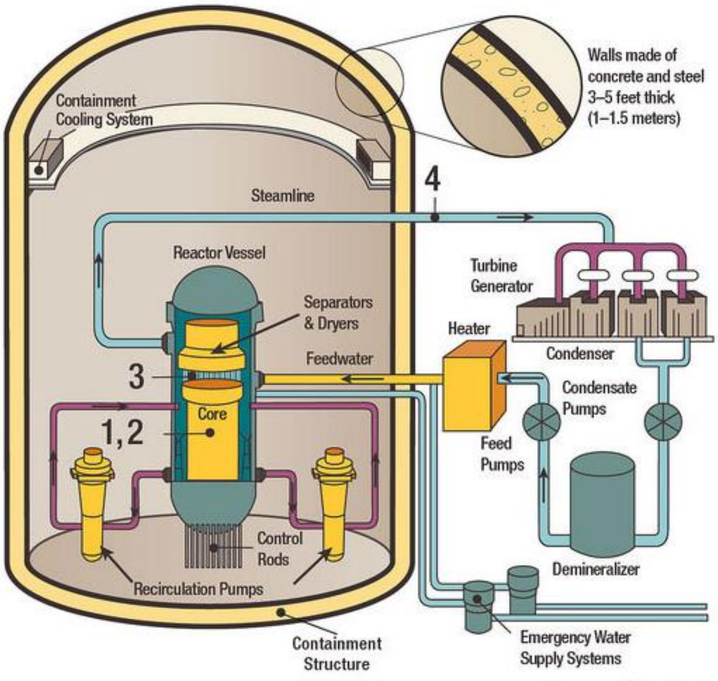


Figure 1 Schematic setup of the BWR process (U.S.NRC)

To control the power generated from the reactor, control rods are used. The control rods are made of a neutron absorbing material, often boron carbide that is protected with a cladding usually consisting of stainless steel. They can be formed in different geometries such as tubes or plates. In the boiling water reactor process the control rods are inserted underneath the reactor core, see Figure 2. The control rods absorb the emitted neutrons, thus decreasing the fission process in the reactor. This leads to a decrease in thermal power which results in less steam and electricity produced (Nuclear power).

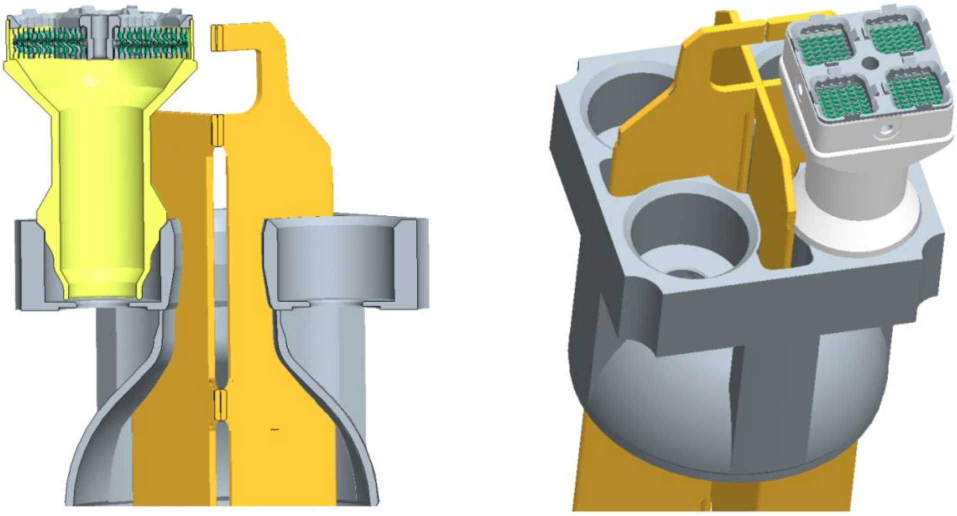


Figure 2 Control rods inserted underneath the reactor core (Westinghouse)

The figure above shows one cell in the grid of the reactor core. One of the four fuel assemblies is presented and the insertion of the control rods underneath the structure can be seen.

2.2 Fuel design

2.2.1 **Currently used fuel design**

One of the currently used fuel designs is called the SVEA-96 Optima3™ and is consisting of four sub-assemblies which can be seen in Figure 3. Each sub-assembly is made up of 10 spacer grids on different levels and the structure of the spacer grid is a 5x5 matrix.

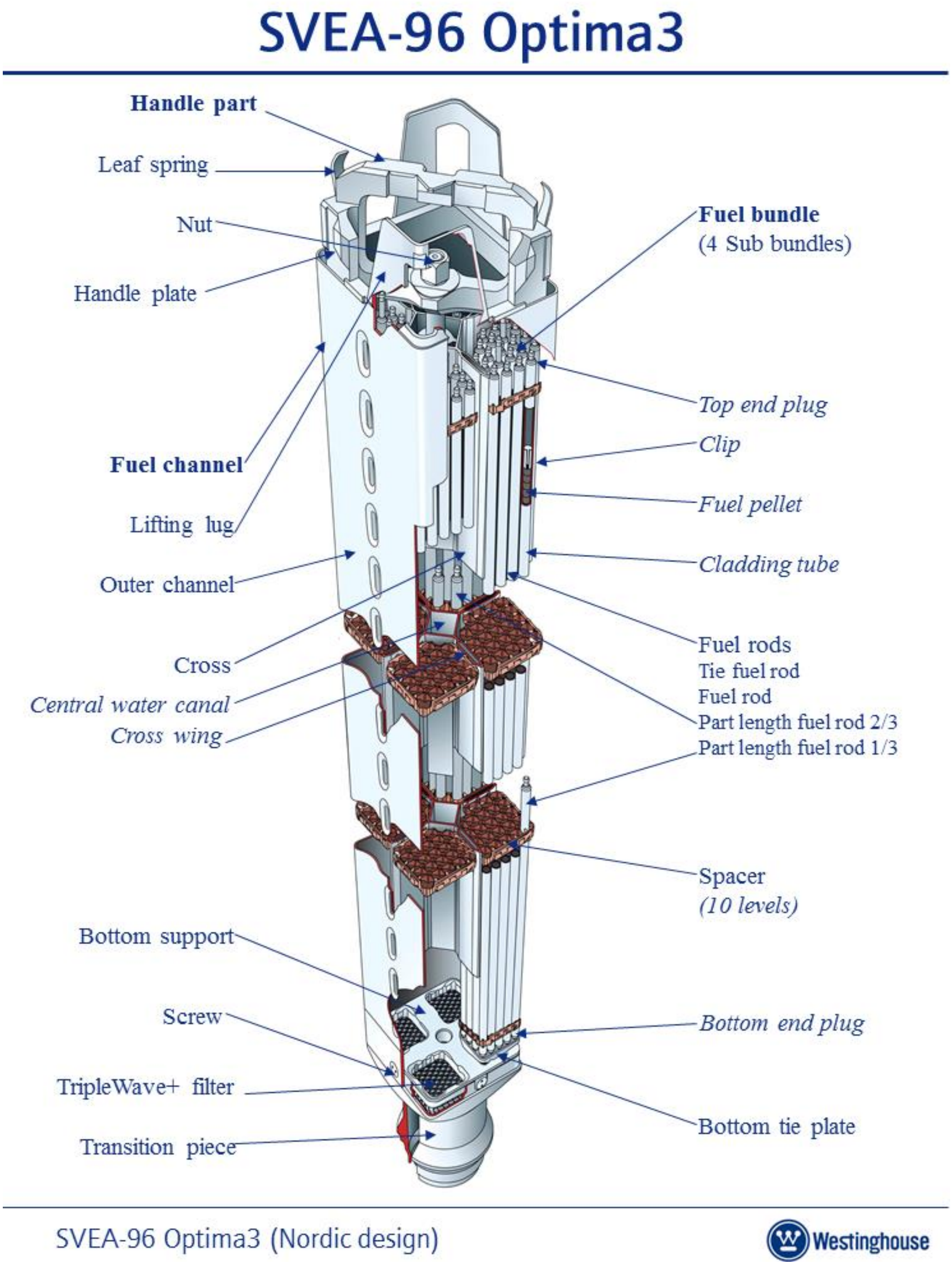


Figure 3 One of the currently used fuel designs (Westinghouse)

The sub-assemblies are filled with fuel rods and there are three different kinds of fuel rods.

The first rod type is the 1/3 rod that has one third of the length of the regular rod and reaches to spacer level 4. Below the fourth level the reactor is said to run on a one-phase flow which means that it is only water in a liquid state. Around level four the water starts to evaporate which leads to an increase in volume. Some of the fuel rods are shortened to account for the expansion and these are the 1/3 rods.

The second type of rods is the 2/3 rod that has two thirds of the length of a regular rod and reaches to spacer level 7. At this level the evaporation has increased further thus demanding more space and the 2/3 rods are shortened to create the extra space needed for the vapor to expand.

The third type of rod is the regular rod that has the full length of about 4 meters.

The design of the spacer grids involves a number of different channels that provides non-boiling water. This water works like a moderator, which means that the speed of the emitted neutrons is slowed down to increase the nuclear chain reaction.

The introduction of the moderator channels leads to a reduction of one cell in the spacer, which means that one sub-assembly can hold 24 fuel rods. This leads to a total of 96 fuel rods in the fuel assembly.

There are two different designs of the SVEA-96 Optima3™ fuel assembly which are the Continental design and the Nordic design.

2.2.2 Continental vs Nordic design

The Continental fuel assembly is designed to fit the reactors made by General Electric and Siemens while the Nordic design is made to fit reactors made by ASEA, (Westinghouse). Only minor changes are done on the internal components between the two fuel assemblies. The main difference between the two designs is the length of the structure and the top and the bottom parts as can be seen in Figure 4.

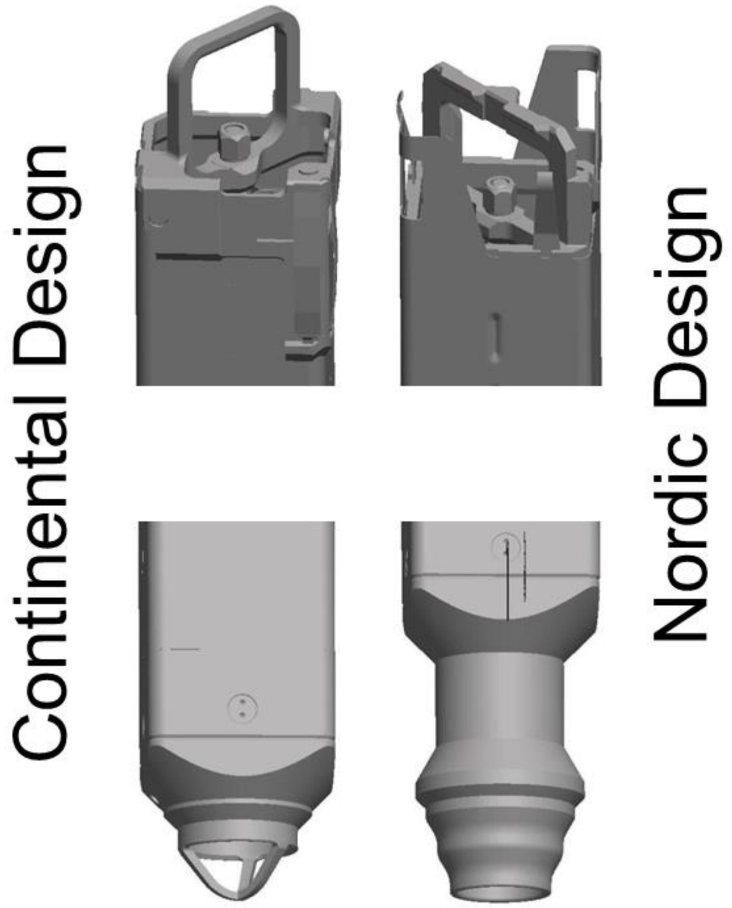


Figure 4 Main difference between Continental & Nordic design (Westinghouse)

The handle of the Continental design has a slightly different design than the Nordic. The total length of the fuel assembly is larger for the Continental than the Nordic.

The difference of the assembly in the reactor core between the two fuel designs can be seen in Figure 5. The figure shows the top part of the reactor where the fuel assemblies are placed in a reactor core grid. Four fuel assemblies are placed in each cell of the grid and the control rods can fit in-between these.

The difference between the two bottom parts can clearly be seen, where the Nordic design has a rounder shape and are a bit longer. This means that the assembly to the reactor core between the two designs differs a bit. The assembly in the reactor core for the Nordic design was presented earlier in Figure 2.

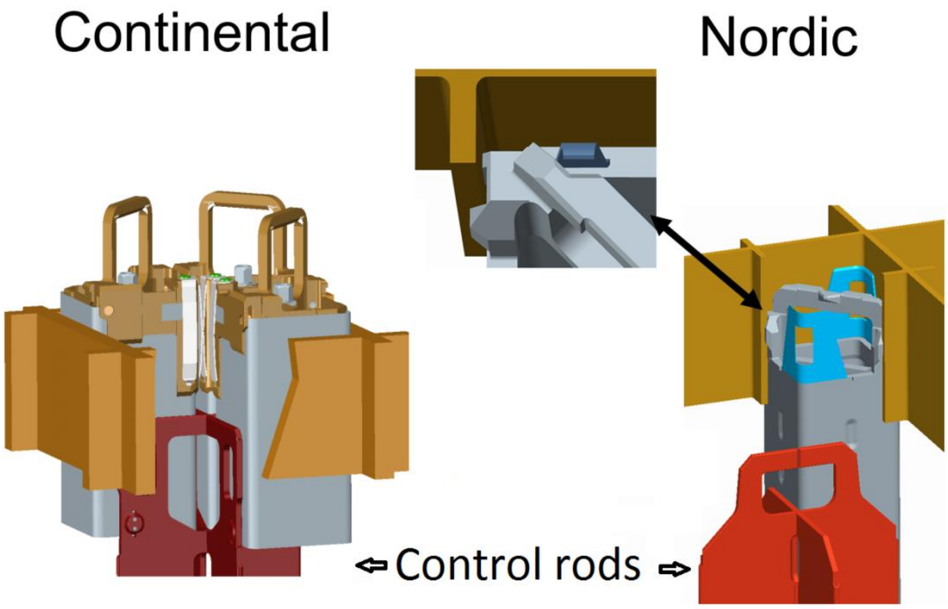


Figure 5 Assembly difference in the reactor core between the Continental & Nordic design (Westinghouse)

As can be seen in the figure above the Continental design is mounted higher than the Nordic.

2.4 Fretting wear

2.4.1 **Grid-to-rod fretting wear**

The fuel rods that are used in the nuclear reactor are placed in an assembly fixture. The assembly fixture contains a number of grids with spacers to keep the fuel rods on a specific distance from each other. The fuel rods are held in place with springs and dimples. The assembly fixture are placed in a metal cower and a top and bottom cover are applied (Westinghouse Electric Sweden AB). Figure 6 shows a possible solution for the fuel assembly grid design and the placement of a fuel rod in one of the grid cells.

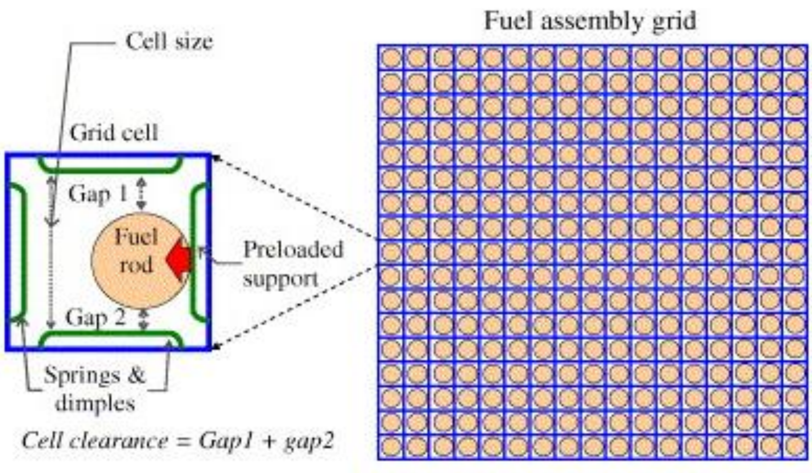


Figure 6 Possible configuration of a fuel grid assembly (Rubiolo, 2006)

Due to the cell clearance the placement of the fuel rod in the grid cell is unknown and may be different for each cell. As a result of this the rod-to-support conditions, preloads and gaps, which effects the fretting wear performance is different for each cell (Rubiolo.2006).

During operation the flow of water creates vibrations in the fixture which causes fretting between the fuel rods and the grid. This is known as grid-to-rod fretting wear which can lead to fuel rod failure. Figure 7 shows the fretting wear for a simplified geometry. The fuel rod is held in place in the grid by a spring to the left and a dimple to the right (Blau, 2014).

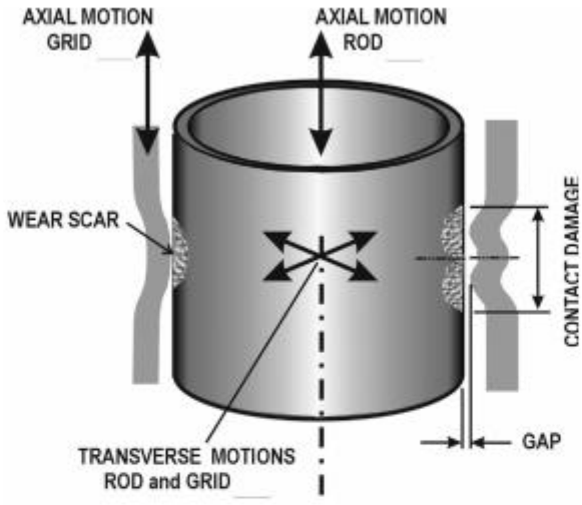


Figure 7 Simplified presentation of the grid-to-rod fretting wear. (Blau, 2014)

It has been found that for the PWR, which is similar to BWR, this fretting wear can be initiated at a critical grid-to-rod gap that depends on the grid design and the vibrations caused by the flow. Tests have shown that the grid-to-rod fretting wear failure can occur anywhere in the axial location of the grid, though it is most frequent in the periphery of the fuel assembly as can be seen in Figure 8 (Kim & Suh, 2009).

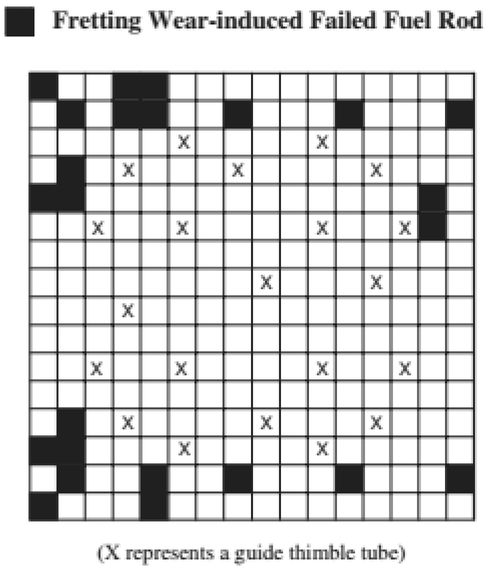


Figure 8 Location of grid-to-rod fretting wear in a PWR fuel assembly. (Kim & Suh, 2009)

2.4.2 Causes for grid-to-rod fretting wear

There are two types of vibrations that are directly related to the grid-to-rod fretting wear. These are the external and internal vibrations. Some of the external vibrations are caused by the configuration of the reactor core such as the axial flow rate and velocity of the reactor coolant, the design of the upper and lower reactor internals and the gap size of the different assemblies.

The internal vibrations can be caused by the water-to-fuel ratio, the spacer grid strap design, the spacer grid mixing vane pattern, the top and bottom nozzle design and the stiffness of the assembly.

The design of the fuel assembly is directly related to the internal vibrations. There are three different kinds of vibrations that may be caused by the fuel assembly design. These are self-excited spacer grid strap vibration, self-excited fuel assembly vibration and excessive fuel rod vibration.

The spacer grid strap vibration is caused by the design of the spacer grid. Some of the parameters that can be changed are the size of the flow window and the thickness of the thin strap. An example of a spacer grid design can be seen in Figure 9.

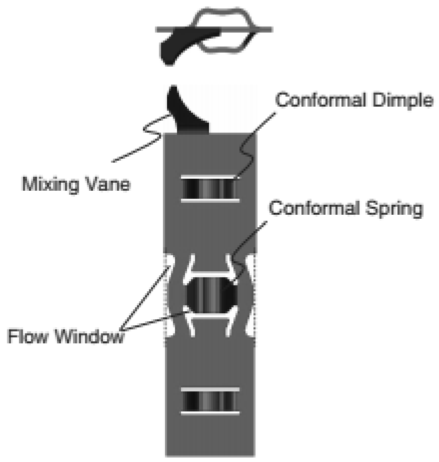


Figure 9 Possible design of a spacer grid. (Kim & Suh, 2009)

The self-excited fuel assembly vibration is caused by an asymmetric mixing vane pattern on the assembly of the spacer grid which leads to a rotational force on the assembly.

The fuel rod vibration is caused by the grid-to-rod gap size. This vibration grows stronger as the gap size is increased (Kim & Suh, 2009).

2.4.3 Other causes for fuel rod failure

It is not only the grid-to-rod fretting wear that can cause the fuel rod to fail. The fuel rods can be damaged during the insertion to the assembly fixture. Some assembly scratches are normal but if the scratches are too deep it can weaken the rods and over time lead to failure.

During operation the fuel rods expand due to irradiation and the thermal expansion. The fuel rods can expand independently from each other which can lead to a misalignment of the spacer grid, which in turn can lead to fretting of the rods.

The welds on the spacer grid can erode from the water and steam mixture. This can lead to an increase of debris in the reactor, which can lead to fretting of the fuel rods. Another source of generating debris is maintenance work in the reactor. The eroded welds weaken the connection between the cells which can lead to increased vibration in the grid.

2.4.4 Minimizing the grid-to-rod fretting wear

Kim & Suh proposes some design guidelines to prevent the grid-to-rod fretting wear caused by the internal vibrations. As mentioned earlier a larger grid-to-rod gap leads to more vibration. To prevent fretting from this source the gap should be minimized.

The fretting caused by the self-excited fuel assembly vibration can be minimized by designing a mixing vane pattern that is hydraulically stable. For example a symmetric pattern is more stable than an asymmetric one.

Fretting from the spacer grid strap can be minimized by designing the springs and dimples to generate a large contact area (Kim & Suh, 2009).

The fretting caused by debris can be minimized by designing a filter to the inlet.

2.5 Method

This project is inspired by the product development and design methodology that has been developed by Ulrich & Eppinger (2012). Due to the nature of the problem only a few steps of the generic process will be used.

2.5.1 **Concept generation**

According to Ulrich & Eppinger (2012) the concept generation phase can be divided into five sub activities. These are

- Clarifying the problem
- Searching externally
- Searching internally
- Explore systematically
- Reflection

The first step in the process is to clarify the problem and understand the critical parameters of the project. Once the problem is well understood it is time to search externally and internally. The external search can be interviewing experts or browsing the internet for useful information. The internal search can be to study earlier similar projects and brainstorming with colleagues.

After the external and internal search a number of different concepts might have been generated. These concepts can be presented in a concept combination table where the problems have been divided into sub problems. The concepts that solve a sub problem are placed in that column and so on. Thus it is possible to combine the different sub solutions to one or a few bigger solutions.

The last thing to do in the concept generation phase is to reflect about the results and to make sure that all solutions have been generated.

2.5.2 **Concept selection**

According to Ulrich & Eppinger (2012) there are several ways to select which concepts to develop further, some of these are

- Intuition
- Prototyping and testing
- External decision
- Decision matrices

Selection by intuition is self-explaining, it can be based on experience or the fact that one concept simply seems better. The prototyping and testing method means that prototypes for each concept are built and tested. Depending on the test results a decision is made. The external selection means that a customer or an external unit makes the decision on which concept to develop further.

Another way of making the selection is by using a decision matrix. This method can be divided into two steps, concept screening and concept scoring. The first step is concept screening which is a coarser and less detailed matrix than the scoring matrix. The concepts that are to be evaluated are placed in different columns in the screening matrix. One concept are set to be a reference and are given the value zero, the reference could be an existing solution to the problem. The remaining concepts are then evaluated from a set of criteria and given a + if it is better than the reference and a – if it is not. At the end the + and – are summed up and the concepts with the highest values are moved to the next step.

An example of a concept screening matrix for the attachment of an intravenous (IV) pole to a bed with three different concepts can be seen in Table 1. Two or more concepts can be combined to eliminate weaker ones, the combined concepts are evaluated in the same manner as the original ones.

Table 1 Concept screening matrix for the attachment of an IV pole

	Lever	Screw joint	Attach to U-beam
Quick assembly	+	0	+
Easy to use	+	0	+
Easy to manufacture	0	0	+
Setting force	0	0	+
Stability	+	0	-
Risk of overturning	0	0	-
Sum	3	0	2
Continue?	Yes	No	Yes

If there is more than one concept remaining after the screening the second stage with concept scoring can be used. The remaining concepts are developed a bit further so more details are known about them. The matrix is formed in the same way as the screening matrix but the evaluation scale is more detailed. A scale from 1 to 5 is recommended where the reference is 3. 1 means that the concept is much worse than the reference and 5 that it is much better. The evaluation criteria are weighted according to how important they are and the sum of all the criteria should be 100%. Each concept is then given a weighted value by multiplying the value with the weight factor and the concept with the highest value is developed further. The same example with the IV pole is used to illustrate the concept scoring matrix and can be seen in Table 2.

Table 2 Concept scoring matrix for the attachment of an IV pole

		Lever		Attach to U-beam	
	Weight factor	Value	Weighted value	Value	Weighted value
Quick assembly	15%	4	0.6	1	0.15
Easy to use	15%	3	0.45	3	0.45
Easy to manufacture	20%	3	0.6	5	1
Setting force	10%	4	0.4	3	0.3
Stability	20%	3	0.6	3	0.6
Risk of overturning	20%	3	0.6	3	0.6
Sum	**100%**		**3.25**		**3.1**
Continue?			**Yes**		**No**

The remaining concept will be developed further. If there is more than one concept remaining after the scoring matrix another selection method should be used. Building prototypes can make the selection easier as the functions of the concepts can be tested. Another method is to present the concepts to an external party, for instance the end users of the product and let them decide which concept to use.

3 Scoping test program

3.1 Understanding the problem

Internal reports, Computer Aided Design (CAD) models and down scaled prototypes have been studied to get a deeper understanding of the problem. A visit to the fuel laboratory has also been conducted. Most of the test program will not be presented due to confidentiality and have been replaced by a cross.

3.1.1 **New design**

The new design is called TRITON11™ and consists of one big fuel assembly instead of the four sub-assemblies that were used earlier. The spacer grid is consisting of an 11x11 matrix and the fuel assembly is made up of 10 spacers on different levels.

Three water rods that reach from the bottom to the top of the fuel assembly provide the moderator water instead of the channels that were used earlier.

One water rod has the size of four cells in the spacer grid, thus leading to a total reduction of 12 cells. The total number of fuel rods in TRITON11™ is 109 which are 13 more than the current design (SVEA-96 Optima3™). This means that TRITON11™ can produce more energy than the current design since both designs have the same outer dimensions of the fuel box.

TRITON11™ comes in both the Continental and the Nordic design.

3.1.2 **The test loop**

The mechanical performance of the fuel assembly design is tested in the test loop BURE. The BURE test loop is a high-pressure loop equipped with ejectors, pumps and heat and steam generators to produce and simulate the operating conditions of the reactor such as the temperature, pressure, flow and steam quality.

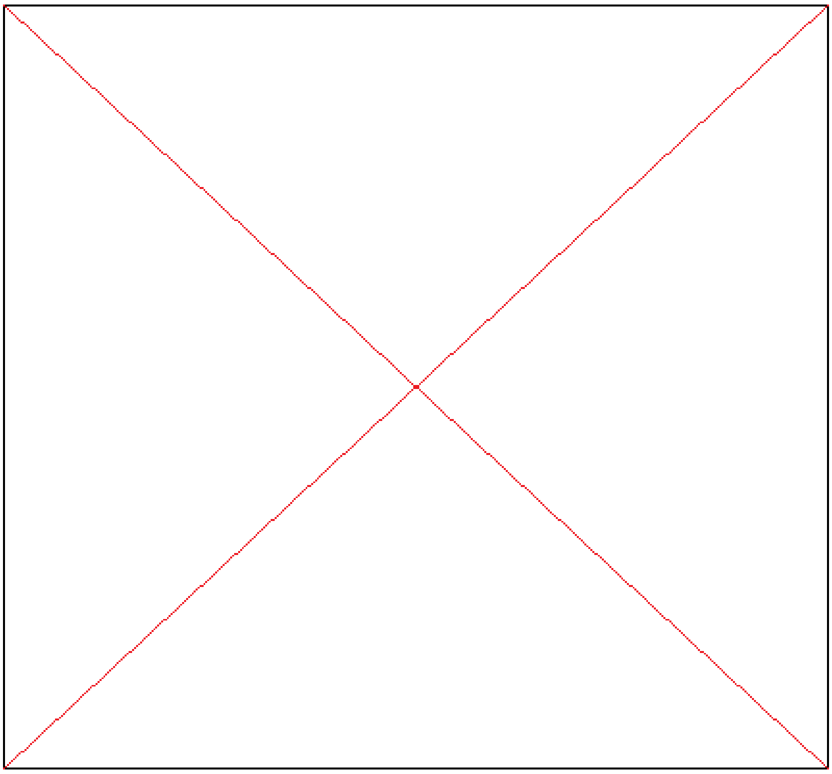
Two different types of tests are performed on the assembly, a scoping test and a verifying test. These tests can in turn be performed with one-phase flow or two-phase flow.

The first test to be run is the scoping test with the purpose of testing the mechanical limitations of the design. After the test the design is refined if needed and a verifying test is performed to verify the mechanical performance.

A one-phase flow test means that the water in the test loop is mainly in one phase, namely liquid. This is used to test the bottom parts and the four first spacer levels in the fuel assembly.

In the two-phase flow the water in the test loop consists of two phases, liquid and gas (steam). This is used to test the top parts and spacer levels five to ten in the fuel assembly.

3.1.3 **Earlier tests**



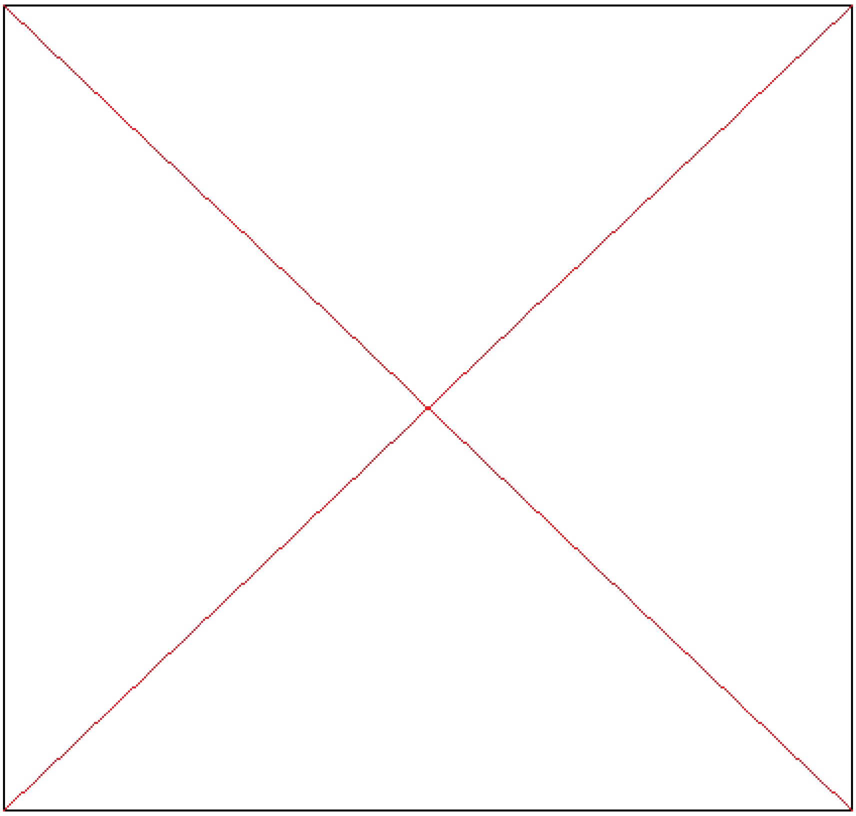
3.2 New testing matrix

The development of the new testing matrix was an iterative process which included studies of the previous work and studies of the part & assembly drawings. The developed test will be a scoping test with two-phase flow conditions.

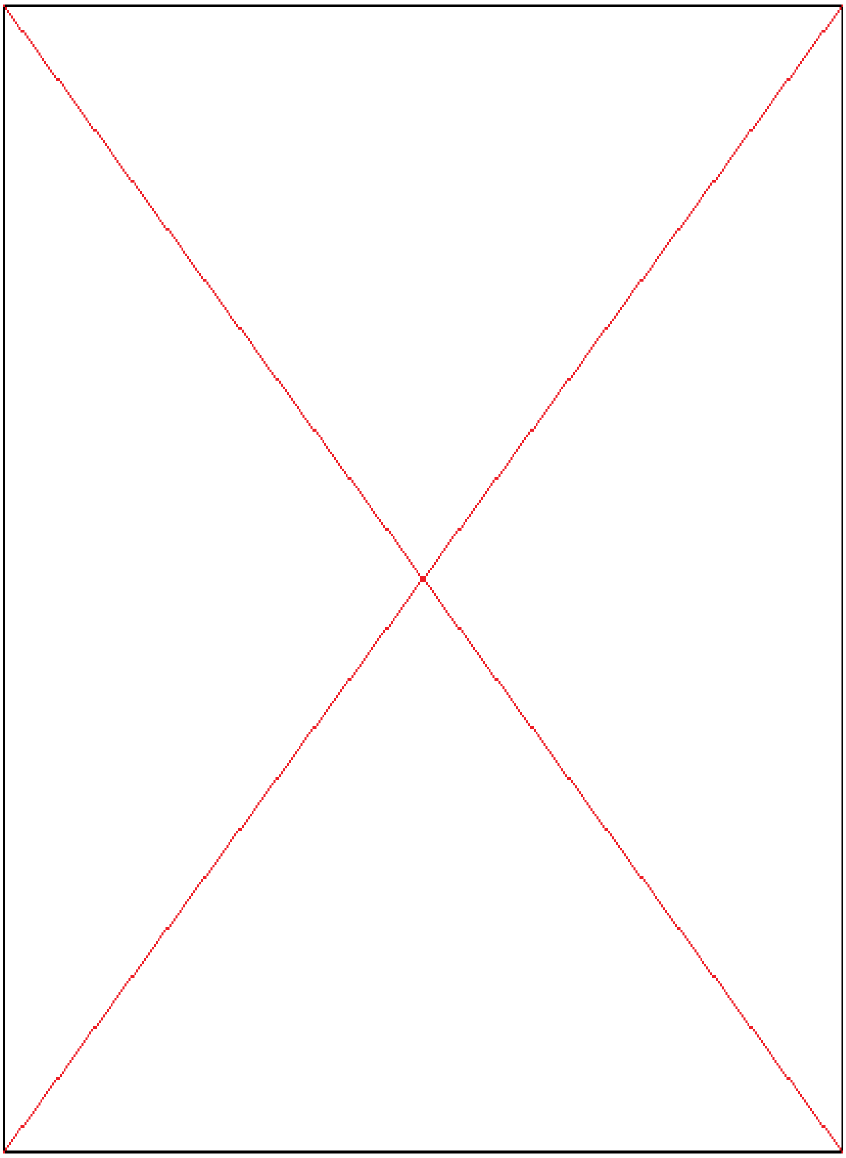
3.2.1 **Concept generation**

From the internal search it was found that some of the previous work could be reused. The selection of the concepts was performed continuously and with the use of intuition and the experience provided by the supervisor Håkan Söderberg.

The following test parameters was reused but with modification.



3.2.2 **Specifying the concepts**



3.2.3 **Test loop conditions**

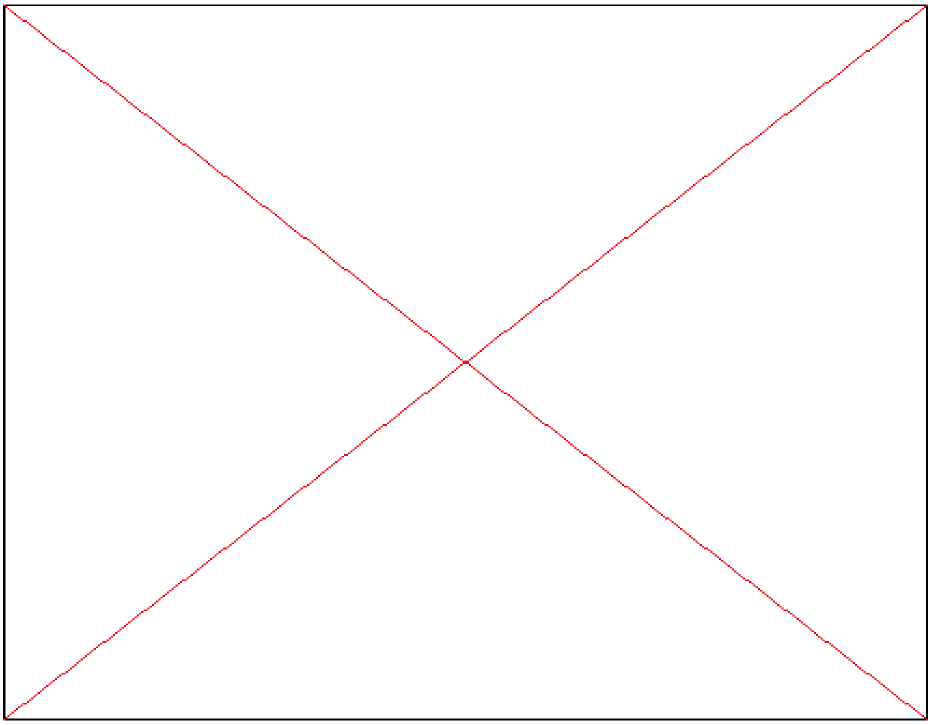
The test conditions are reused from earlier tests without any modification. Two-phase flow conditions will be used to test the components from spacer level five to ten. These conditions are represented in the test loop by keeping the temperature at around 280°C and the pressure at 70 bar. The flow should be kept constant with 19 kg/s and with a steam ratio of 15%. The test should be performed under these conditions for at least 700 hours.

To ensure that these conditions are met the test data should be registered once per hour.

3.2.4 **Test setup overview**

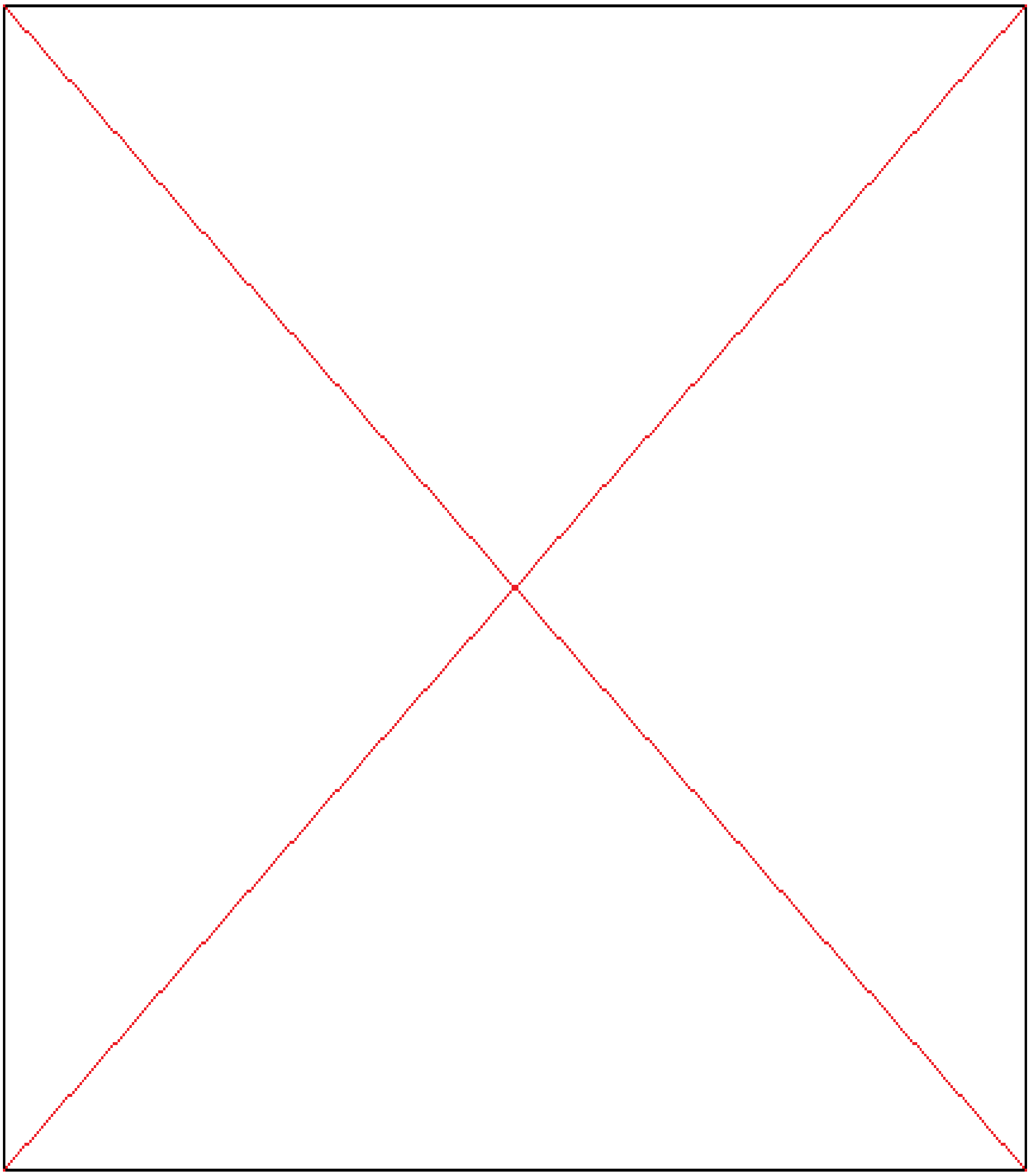
The specifications derived in the previous chapter are summarized in the following chapter.

The overview of the test setup for TRITON11™ is presented in the table below.

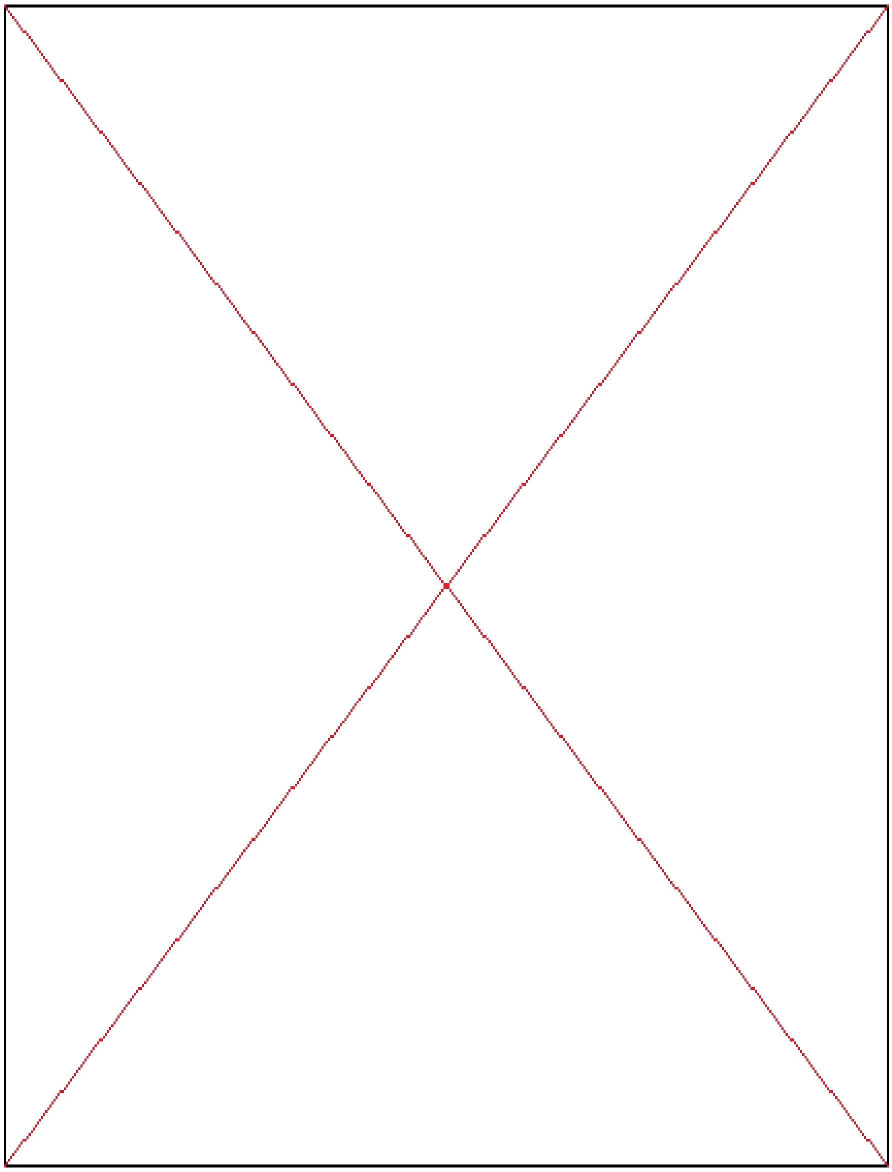


3.2.4.1 Grid-to-rod gaps

The grid-to-rod gaps and grip in the different positions of the spacer levels are presented in the following table.



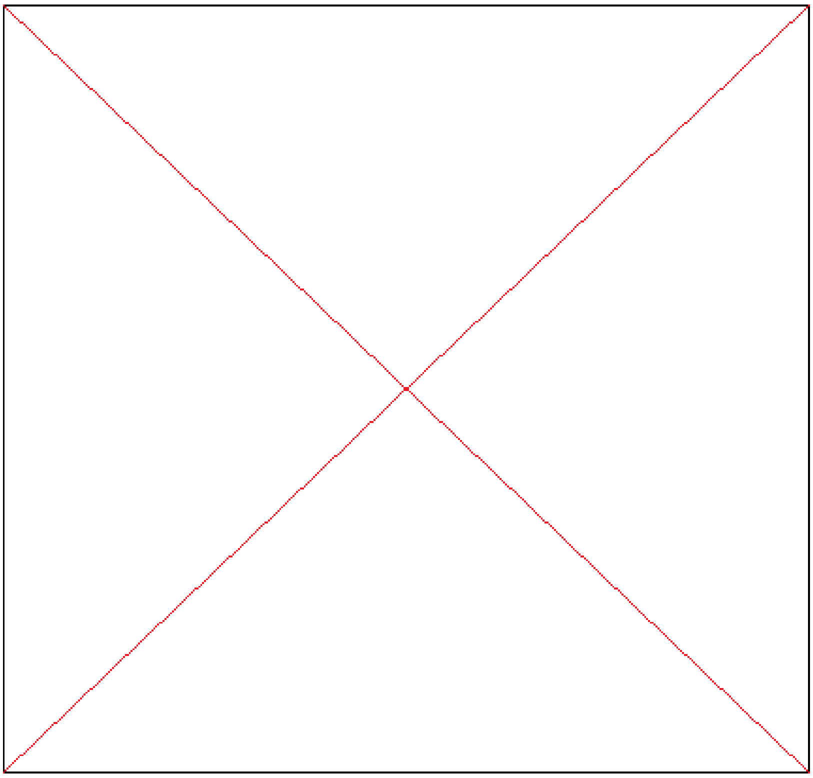
3.2.4.2 Removed welds



3.3 Test Components

The components used in this scoping test will mainly consist of the Nordic design. The test fuel rods that are used are a bit longer than the Nordic full length rods, but shorter than the Continental full length rods. The channel that covers the fuel assembly needs to be adjusted in length to compensate for the longer rods. The modification is done on the top part of the channel and the changes will not affect the performance substantially.

The length of the water rods are also adjusted to compensate for the longer fuel rods. The water rods are designed with bulges to prevent the spacer from moving to far away from their initial position. The bulges should work as an extra precaution, but the spacers should be held in place by the water rods and the fuel rods. The water rods used in the scoping test are simplified by removing the bulges. This should not affect the results since the spacers should still be held in place.



4 Development of the assembly fixture

To assemble the fuel bundle for the test a new fixture had to be constructed. A visit to the fuel laboratory was made to investigate the current solution and discussions were made with the personnel that would use the fixture.

4.1 Understanding the problem

The purpose of the assembly fixture is to hold the spacers in place while the fuel and water rods are assembled. The spacer's needs to be held in place firmly to avoid any misalignments of the cells and it should be possible to adjust the position of the spacers in the vertical direction. The fuel bundle is assembled in the vertical direction and the bottom plate should fit in the fixture and be assembled with the water rods. The fixture should fit both the Nordic and the Continental design to save space and money. The overall cost of the structure should be kept down.

4.1.1.1 Product specifications

The product specifications have been derived from the discussions with the personnel at the fuel laboratory and are presented in Table 3. The specifications are given a number from one to five depending on how important they are, where 1 is not important and 5 is very important.

Table 3 Product specifications

Specification	Importance
The spacer must be kept firmly in position	5
The spacer can be adjusted in the vertical direction	5
Both the Nordic and the Continental design can be assembled in the structure	5
The structure is easy to use	4
The cost of the structure is low	4

4.1.1.2 Problem breakdown

The problem of developing a new assembly fixture for TRITON11™ could be divided into smaller sub problems. Four different sub problems could be identified and these were

- Fixture frame
- Level adjustment
- Spacer holder
- Bottom plate holder

The solution for a sub problem could affect the possible solutions for the remaining ones. This needed to be kept in mind during the process.

4.2 Concept generation

4.2.1.1 Fixture frame

The frame needed to fit the spacers, spacer holders and the bottom plate. A number of different cross sections were generated by brainstorming. Most of the generated concepts were eliminated by intuition and two concepts remained after the first elimination. These are presented in Figure 10. The wall thicknesses for the two profiles are the same.

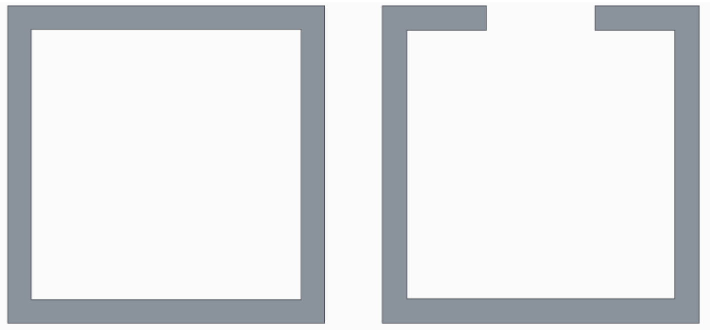


Figure 10 The two remaining cross sections after the first elimination

The cross section to the left, concept 1, is a simple rectangular profile and the idea is to fit the spacers inside. Large rectangular holes are cut along the sides to be able to adjust the position of the spacer holders. Some material is kept at different levels to increase the stiffness of the structure, see Figure 11.

Figure 11 Fixture frame for concept 1

The other cross section is open and the idea is to place one in each corner and connect them with a few rectangular frames at different positions. Two of the frame openings are facing outwards and two are facing inwards, see Figure 12.

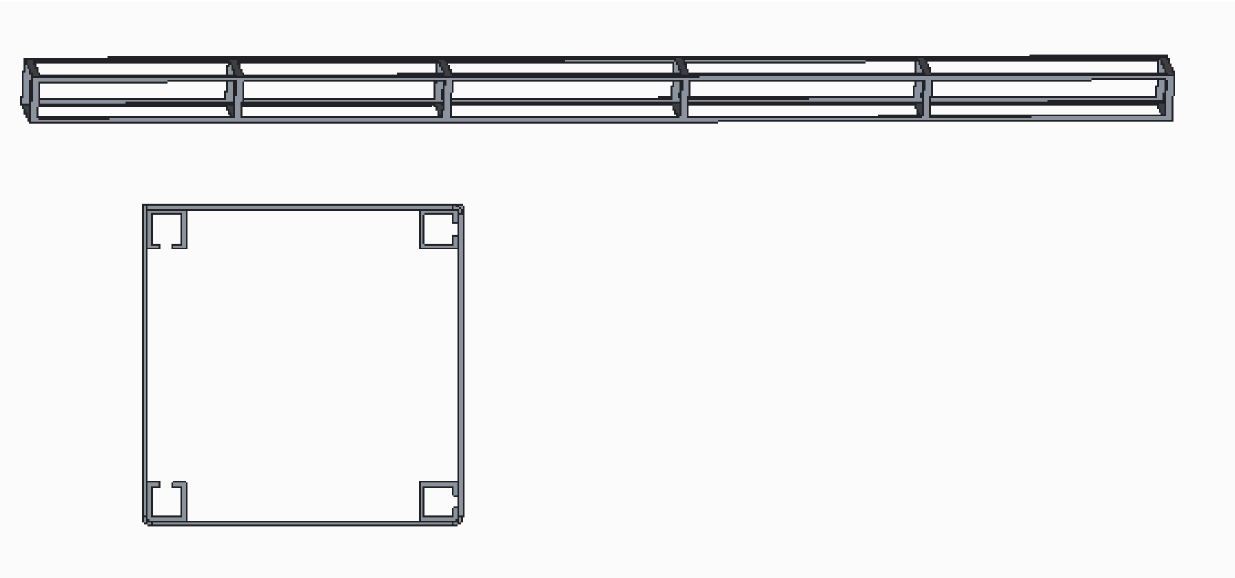


Figure 12 Fixture frame for concept 2

4.2.1.2 Level adjustment

A number of different concepts were generated but some could be eliminated at an early stage. Four different concepts remained to solve the problem with the level adjustment. The first concept was to drill holes along the vertical direction of the frame. Rods would be inserted to the holes and the spacer holder would rest on top of the rods. The concept can be seen in Figure 13.

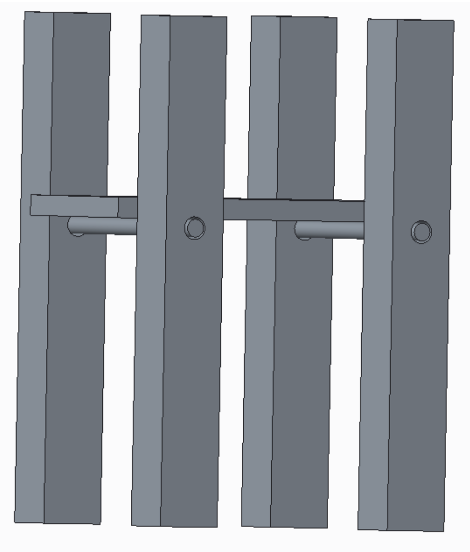


Figure 13 Concept 1 for level adjustment

The second concept was to use a frame formed like a U with a joint and a lever. The frame is mounted on the outside of the assembly frame and can then be locked in place by the lever. The spacer holder would then be placed on top of the U-frame, the concept can be seen in Figure 14.

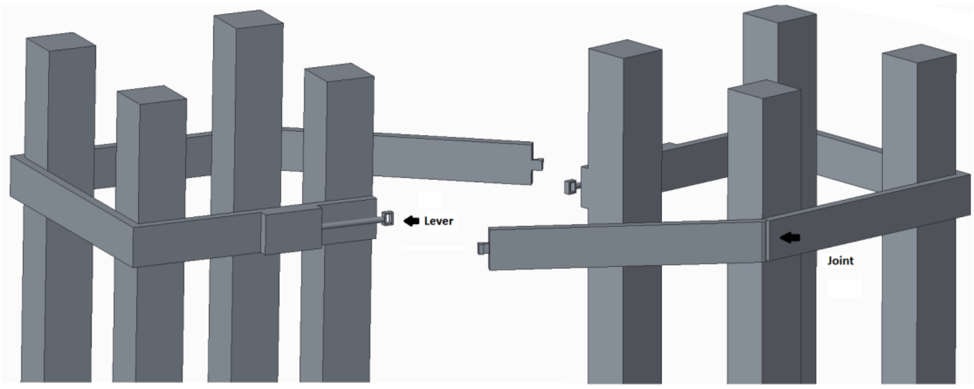


Figure 14 Concept 2 for level adjustment

The third concept required the frame with the closed cross section. A U-frame would be placed outside of the assembly frame and a short plate with two screws would be placed on the inside. These would secure the U-frame that is clamped together with two nuts, the concept can be seen in Figure 15. The spacer holder is placed on top of the U-frame.

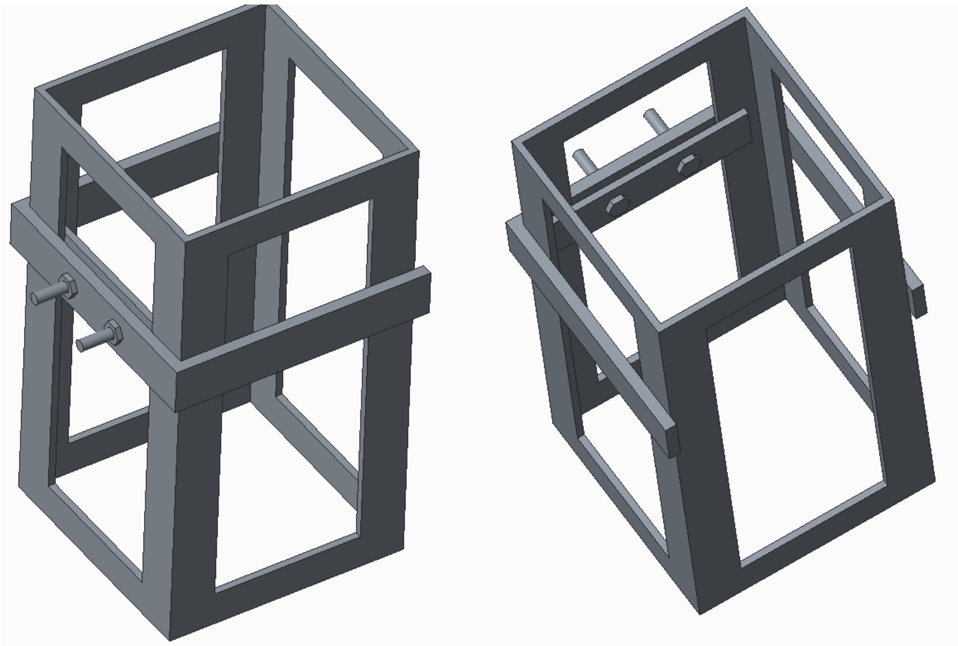


Figure 15 Concept 3 for level adjustment

The fourth and last concept is similar so the third but uses the other frame profile. A U-frame is placed outside of the assembly frame. Two small plates with screws are placed inside the open profile of the frame. These holds the U-frame in place and are secured by two nuts, the concept can be seen in Figure 16. The spacer holder is placed on top of the U-frame.

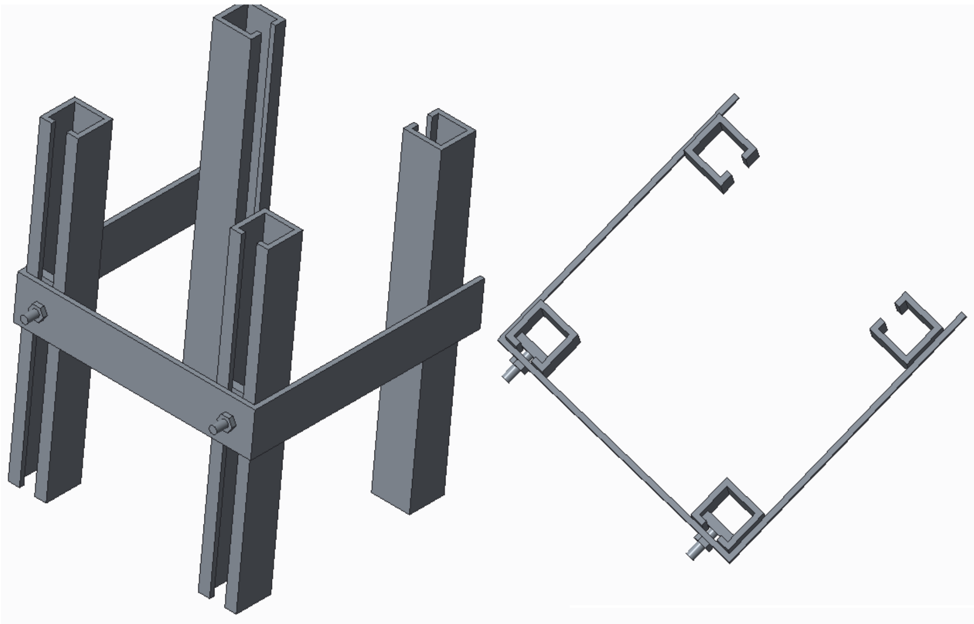


Figure 16 Concept 4 for level adjustment

4.2.1.3 Spacer holder

The spacer holder needs to hold the spacer firmly during the assembly and it should be possible to remove the holder easily after the assembly is done. By studying the previous solutions two similar concepts were generated.

The first concept was a simple design consisting of three flat bars welded together, see Figure 17.

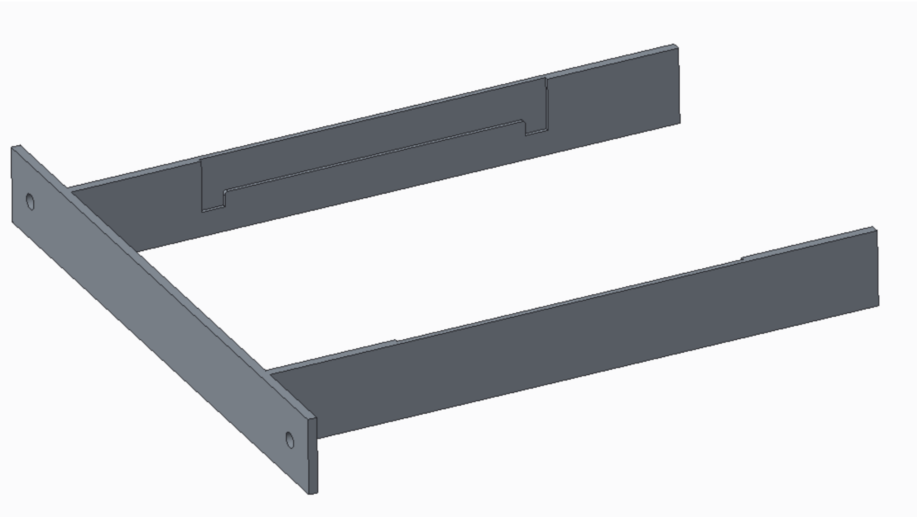


Figure 17 Concept 1 for spacer holder

A simplified outer profile for the spacer has been milled on the two bars that are perpendicular to the base. The spacer is placed in between the two bars. The spacer holder can be mounted to the frame like the concepts shown in Figure 15 and Figure 16 by adjusting the position of the screw holes shown in Figure 17.

The second concept consists of a thick plate that is cut and milled to fit the spacer. The simplified outer profile of the spacer has been used here as well. A track has been milled near the edges of two of the sides to mount the spacer holder to the level adjustment frame. An end piece is mounted to the spacer holder to create a closed section where the spacer is placed. The concept can be seen in Figure 18.

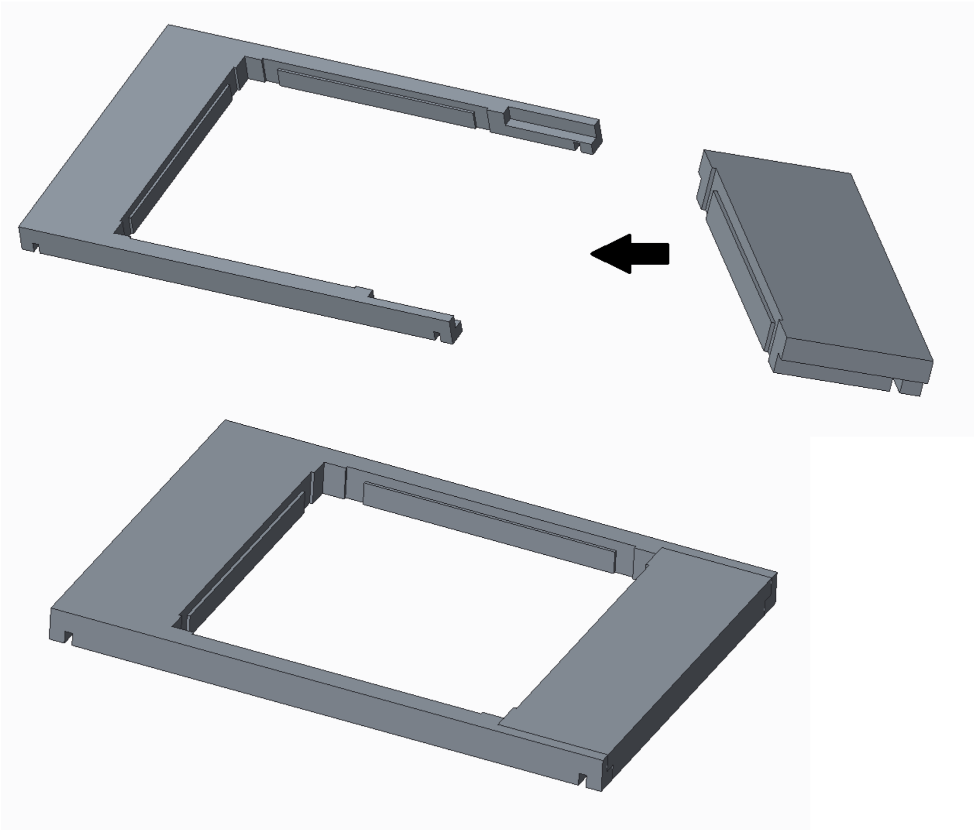


Figure 18 Concept 2 for the spacer holder

4.2.1.4 Bottom plate holder

The design of the bottom plate for the Nordic and Continental design is similar to each other. They both have the same outer dimensions but the Continental is a bit higher and has a variable cross section.

The bottom plate holder should be able to hold the two different designs. It should also be possible to assemble the bolts to the water rods from underneath the holder.

Two concepts were generated to solve the problem. The design of the two concepts is the same, but the material and thickness of the holder is different.

The first solution is a thick steel plate that has been milled to fit the profile of the two bottom plates. A large rectangular hole has been done in the middle to allow the water rod bolts to be assembled. The holder is welded directly to the fixture frame as can be seen in Figure 19.

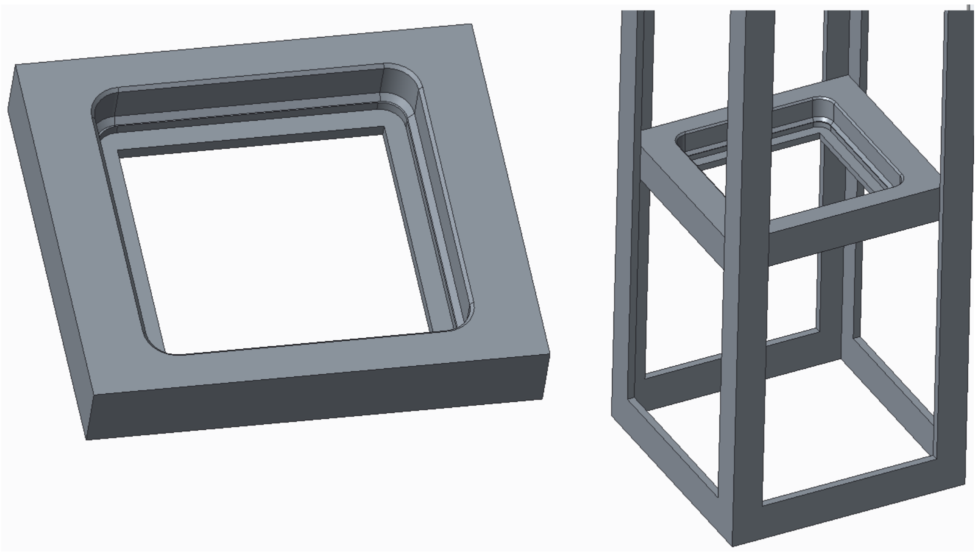


Figure 19 Concept with steel for the bottom plate holder

The second solution is to change the material to polyoxymethylene (POM) which is an engineering thermoplastic. The plastic bottom holder is a bit thicker than the one in steel to make sure that it will not break from the loads. The holder is attached to the fixture frame by placing it on top of four brackets, one in each corner. The concept can be seen in Figure 20.

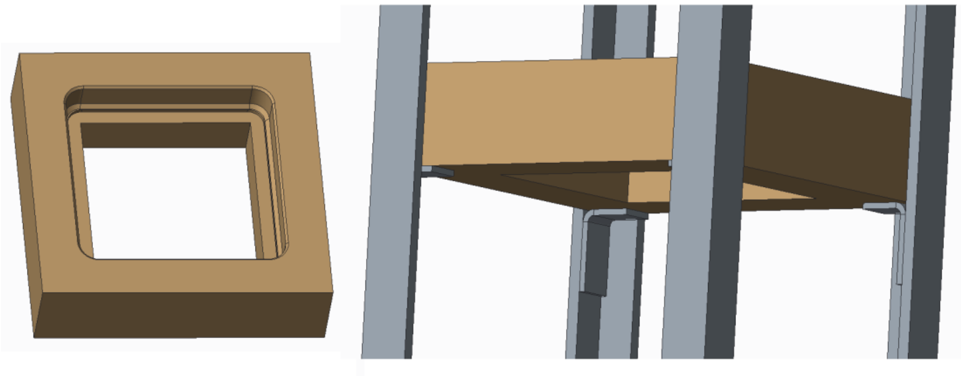


Figure 20 Concept with POM for the bottom plate holder

4.3 Concept Selection

4.3.1.1 Fixture frame

The first concept with the closed section is easier and cheaper to manufacture than the second one with the open section. This is because the profile is standard, the rectangular holes could be made by water or laser cutting. The other concept required the four corners to be welded on to a few rectangular frames, thus increasing the number of parts.

Although the first concept is easier to manufacture they both have potential to solve the problem equally well. Therefore, none of the concepts are eliminated at this stage.

4.3.1.2 Level adjustment

A concept screening matrix, Table 5, was made for the selection of the level adjustment. The third concept was set to be the reference and was given the value 0. The criteria's used in the screening matrix are described in Table 4.

Table 4 Description of the screening criteria's

Criteria	Description
Easy to manufacture	How easy the component is to manufacture. The cost of the component is directly affected by the manufacturing.
Easy to assemble	How easy the component is to mount on the fixture frame.
Precise adjustment	How precise the level can be adjusted.
Applied load	How much load the component can hold before it loses its position.

Table 5 Concept screening matrix for the level adjustment

Criteria	Concept 1 (Rods)	Concept 2 (Joint & Lever)	Concept 3 (ref) (U-frame)	Concept 4 (U-frame)
Easy to manufacture	+	-	0	0
Easy to assemble	+	-	0	0
Precise adjustment	-	0	0	0
Applied load	+	0	0	0
Stability	+	0	0	0
Sum	3	-2	0	0
Continue	**No***	**No**	**Yes**	**Yes**

* Concept 1 got the highest score since it is just two rods that are easy to manufacture and assemble. It got a negative score on precise adjustment and since this is an important requirement it was decided to eliminate the concept.

The concept that was developed further was concept 3 and 4. They are both quite similar but concept 3 is made to fit the fixture frame with the closed section and concept 4 is made to fit the other fixture frame.

4.3.1.3 Spacer holder

The first concept with the three welded bars is easier and cheaper to manufacture than the second concept but only supports the spacers firmly on two sides. Due to the design it does not need the level adjustment frame if mounted to the fixture frame in concept 2, this would reduce the amount of parts. By adding a track like the one used in concept 2 it can be mounted on the level adjustment concept 3.

The second concept requires milling on two parts to create the required features. It holds the spacers firmly on all sides which are desired. The spacer holder is easy to mount on the level adjustment frame and does not need any redesigning to fit both fixture frames.

None of the two concepts is eliminated at this stage since both could solve the problem well.

4.3.1.4 Bottom plate holder

The plastic bottom plate holder was chosen because it is cheaper and easier to manufacture than the one in steel. Since it is not welded to the fixture frame it can easily be replaced if so is needed. It would also be easier to adjust the position of the holder if needed. The low density of POM reduces the weight of the holder significantly compared to steel.

4.4 Combined solutions

Two designs were developed by using the previous mentioned components. The first design consisted of the components shown in Table 6.

Table 6 Components in the first concept

Concept 1	
Component	**Concept**
Fixture frame	2 – Open cross section
Level adjustment	None*
Spacer holder	1 – Three flat bars
Bottom plate holder	2 – Plastic holder

* The level adjustment is done directly by the spacer holder by using parts from concept 4 of the level adjustment. The small plates inside the cross section of the fixture frame are attached to the spacer holder.

To minimize the deflection of the spacer holders a simple plate was added on the opposite side of the base, allowing the free ends of the spacer holders to rest on the plate.

Standard components such as screws and wing nuts were used. The wing nuts were chosen to simplify the level adjustment. The concept can be seen in Figure 21.

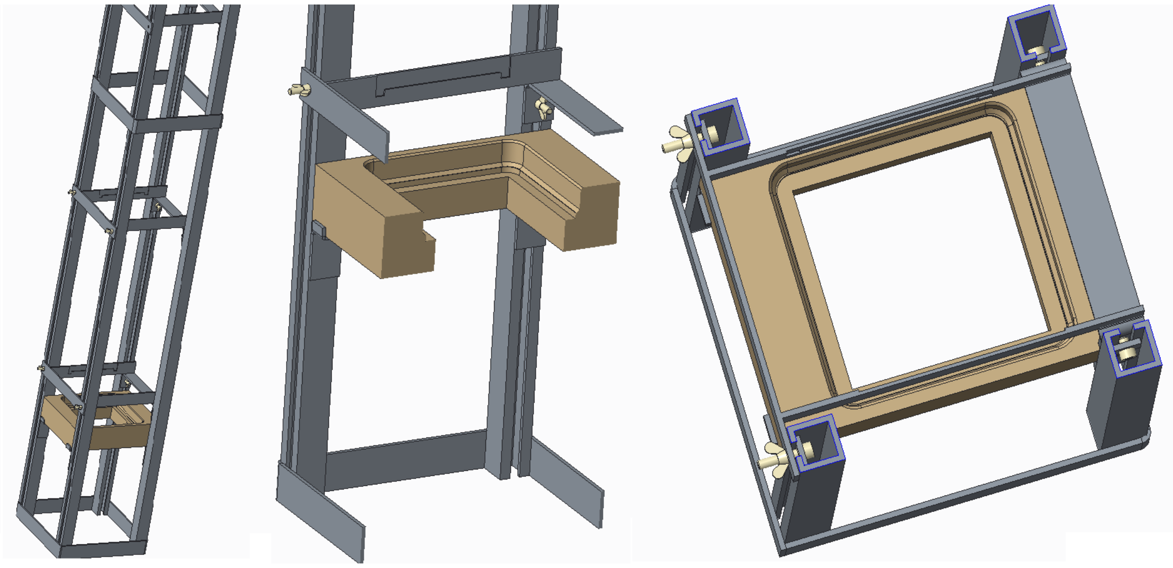


Figure 21 Concept 1

As can be seen in the figure above the level adjustment of the spacer holder and the counter plate is done directly on the frame. The spacer holder is to the left in all three images.

The second concept consisted of the components shown in Table 7.

Table 7 Components of the second concept

Concept 2	
Component	**Concept**
Fixture frame	1 – Closed cross section
Level adjustment	3 – U-frame
Spacer holder	2 – Plate
Bottom plate holder	2 – Plastic holder

A simple plate was added to minimize the deflection of the level adjustment frame. It is fastened in the same way as for the level adjustment frame. The concept can be seen in Figure 22.

Screws and wing nuts have also been used in this concept to fasten the different parts and allow for easy adjustment.

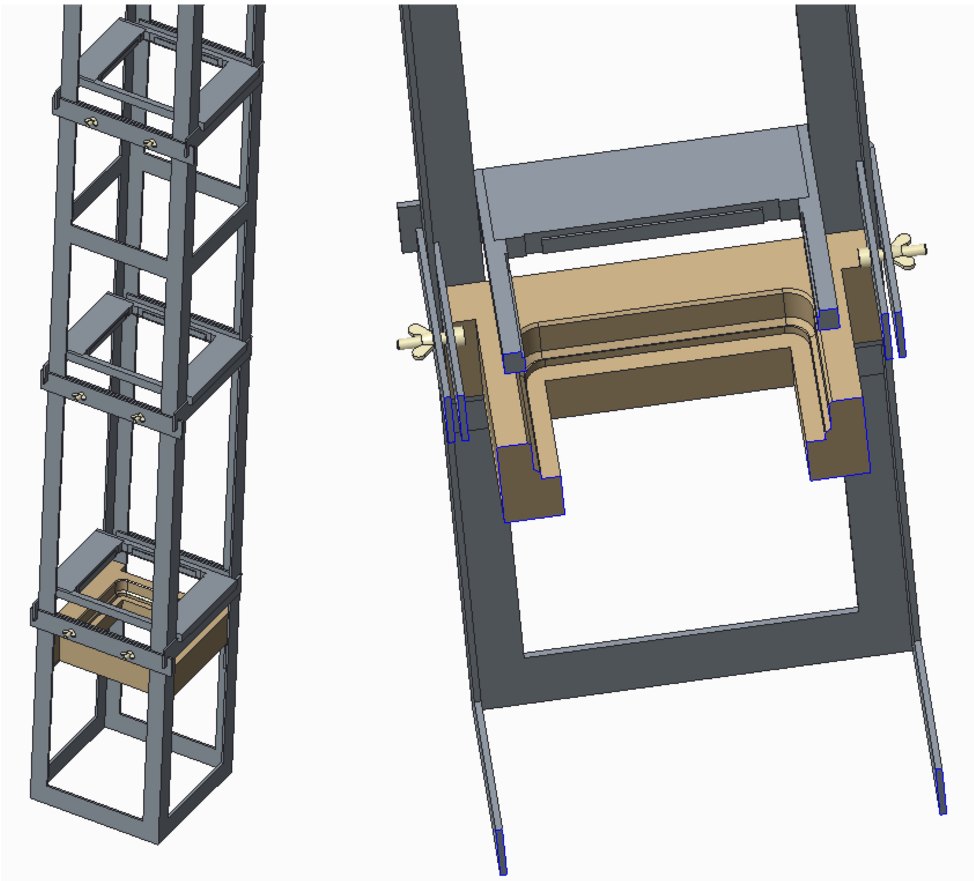


Figure 22 Concept 2

4.5 Further development

The two concepts were presented at an engineering review where two installers and the chief of thermohydraulics were present. From the review it was decided to continue with a combination of the two concepts. Furthermore a new requirement was introduced, the channel box and transition piece of the continental design should be able to be assembled in the fixture.

4.5.1 **Redesigning**

From the engineering review it was decided to use the second concept of the fixture frame, the open cross section. This is because the other concept required the frame to be cut by laser or water, which could make the structure skew. Furthermore all the sharp edges would have needed to be rounded to avoid injuries of the installers.

The level adjustment concept 4 were reintroduced and modified.

The second spacer holder concept would also be reused since it supports the spacers on all four sides.

The plastic bottom plate holder should be reused but with small modifications.

To be able to assemble the Continental transition piece a holder needed to be designed. The inner dimensions formed by the fixture frame are large enough to fit the channel.

The components used in the combined concept are presented in the following chapters.

4.5.1.1 Fixture frame

An extended benchmarking was performed to find standard profiles and suppliers that were similar to the profile from concept 1.

From the benchmark it was decided to use the standard item profile system by AluFlex AB. The profile is made of aluminum and can be seen in Figure 23. Four profiles are used to build the fixture frame, one in each corner.

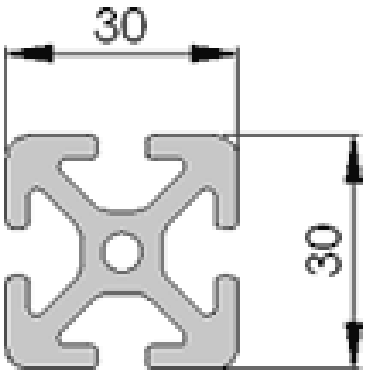


Figure 23 Used profile for the fixture frame (AluFlex AB)

4.5.1.2 Frame connectors

To connect the four corners of the fixture a frame connector was used. The outer dimensions formed by the four corners were 210x210 mm. No rectangular standard profile in aluminum or stainless steel with the dimensions mentioned above could be found during the benchmarking. Thus the rectangular frames used in concept 1 could not be reused.

To connect the corners a flat bar is bent with 90 degrees and four holes are drilled as shown in Figure 24.

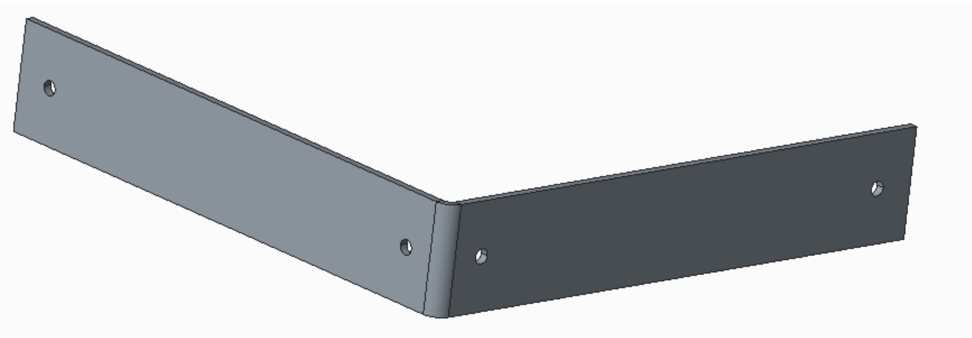


Figure 24 Bent bar to connect the corners of the fixture frame

Two of the bent bars are used to form a rectangular frame. Each corner is fastened with two screws for extra stability. The assembly of the frame connectors and the corners can be seen in Figure 25.

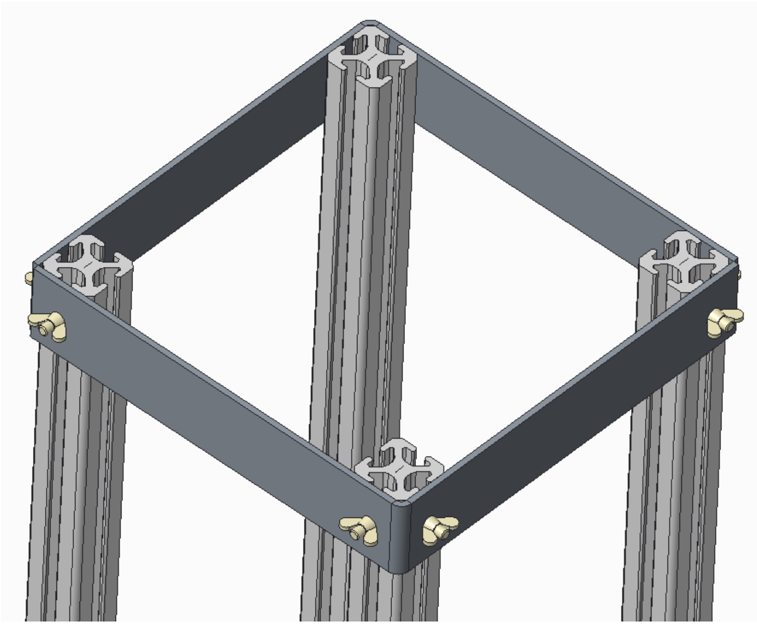


Figure 25 Assembly of the frame connectors and the corners

4.5.1.3 Level adjustment

The level adjustment concept 4, U-frame, was reused but with small modifications. Two extra holes were added to the sides of the U-frame. This leads to better stability and the elimination of the counter holder. The U-frame can be used on all levels except the first one that is closest to the bottom plate holder. That is because the U-frame would intersect with the bottom plate holder when the bottom spacer is at its lowest position, the U-frame can be seen in Figure 26.

The interfering problem is solved by adjusting the height of the bottom spacer with two simple plates instead of the U-frame, the plate can be seen in Figure 27

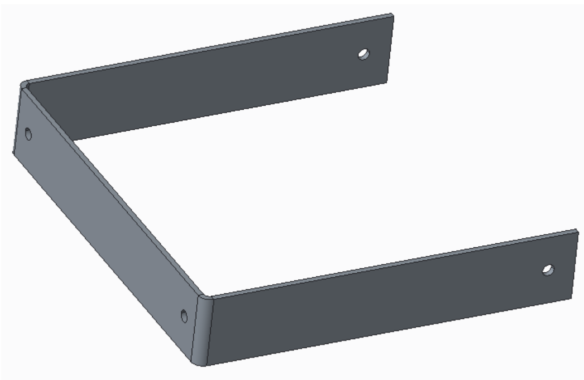


Figure 26 U-Frame for level adjustment

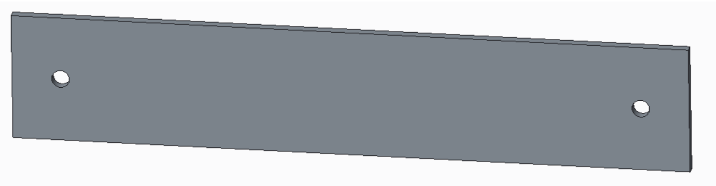


Figure 27 Level adjustment for bottom spacer

4.5.1.4 Spacer holder

The spacer holder remains mainly unchanged and can be seen in Figure 18. The length of the spacer holder is adjusted to fit the level adjustment frame.

4.5.1.5 Bottom plate holder

The bottom plate holder remains mostly the same. The length has been increased and two tracks have been added to mount the holder to the level adjustment plate in the same way as for the spacer holder. The corners have been removed to increase the distance to the wing nuts on the level adjustment frame. The new bottom plate holder can be seen in Figure 28.

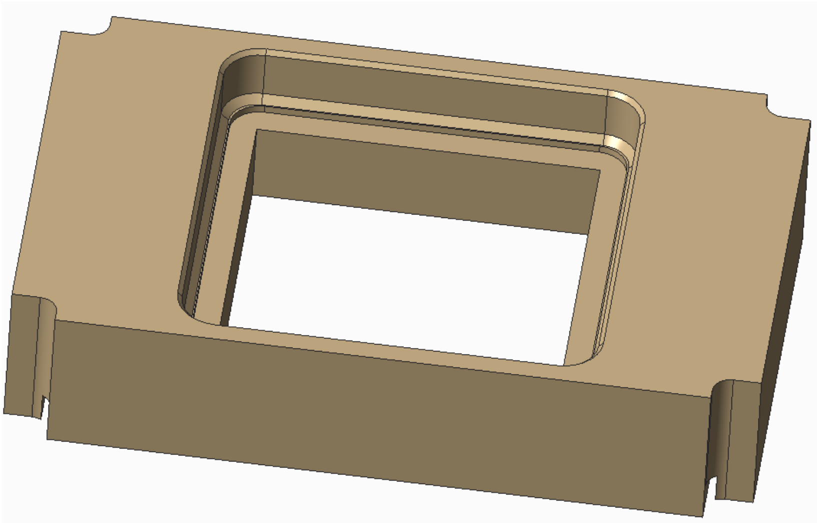


Figure 28 Modified bottom plate holder

4.5.1.6 Screws

The screws that are used are fully threaded according to ISO4017 and are of the dimensions M6x20. M6 screws are the largest screws that can be fitted inside the fixture frame.

The screws that hold the bottom plate holder in place are the ones that are loaded the most. They need to support the whole weight of the fuel bundle, which is approximately 280 kg. A rough estimation of the strength in the joint is presented in appendix A.

4.5.1.7 Continental Transition Holder

Some different concepts were generated to solve the problem with the holder for the Continental transition piece. The transition piece is fastened to the bottom plate with four screws, therefore there has to be sufficient clearance for the tool when the holder is placed inside the fixture frame. Two of the concepts were developed further and are presented in this chapter.

The first concept is a tube in stainless steel that has a chamfer on the top edge. The circular bottom part of the transition piece is inserted to the tube. The transition piece can be rotated 360° in the holder. It must therefore be manually aligned to the bottom plate in which it will be fastened. The position of the holder inside the frame must also be aligned manually to the bottom plate. The concept can be seen in Figure 29.

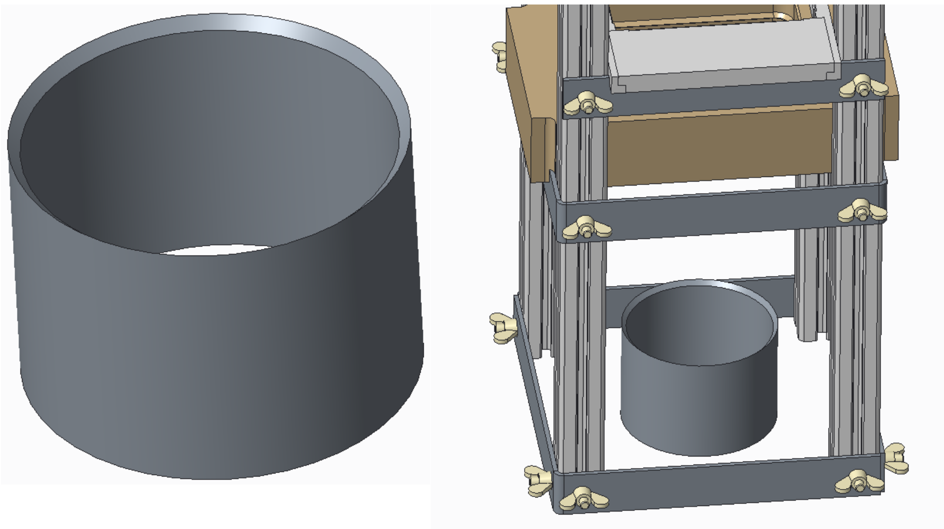


Figure 29 The first concept for the transition holder. The placement of the holder inside the fixture frame can be seen to the right.

The second concept is a bit more complex and follows the contours of the transition piece. The holder is created in POM to reduce the weight of the part. It has four straight walls on the top to adjust the position of the transition piece, thus it will always be correctly aligned to the bottom plate. The bottom of the holder is designed to be correctly aligned when placed inside of the fixture frame. The concept can be seen in Figure 30.

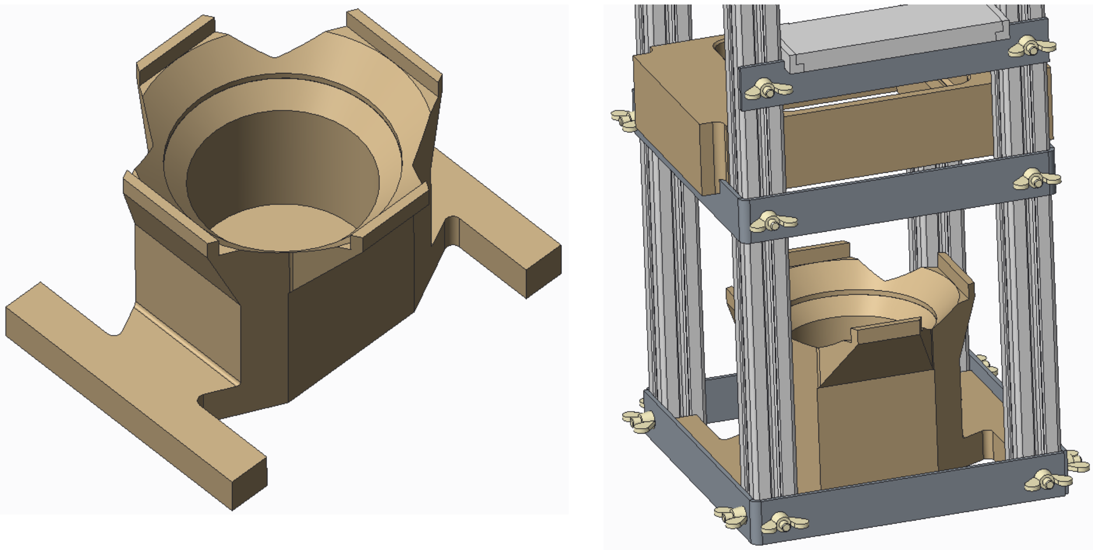


Figure 30 The second concept for the transition holder. The placement of the holder inside the fixture frame can be seen to the right.

4.5.1.7.1 Transition Holder selection

A concept screening matrix, Table 9, was used to select between the two designs. The criteria's used for the selection are described in Table 8. The second concept with the holder made in POM was set as reference and given the value 0.

Table 8 Description of the screening criteria's

Criteria	Description
Easy assembly	How easy it is to align the component in the holder to the bottom plate. Also how easy the holder is to align correctly inside the fixture frame.
Stability	How stable the holder is with respect to overturning
Easy to manufacture	How easy the component is to manufacture. The cost of the component is directly affected by the manufacturing.
Design change sensitivity	How sensitive the component is to minor design changes of the transition piece

Table 9 Concept screening matrix for the Continental transition holder

Criteria	Concept 1- steel tube	Concept 2 – POM holder
Easy assembly	-	0
Stability	-	0
Easy to manufacture	+	0
Design change sensitivity	+	0
SUM	0	0
Continue?	Yes	No*

* The second concept will not be used since it would be more expensive to manufacture than the other one. The design is also more sensitive to changes in the design of the transition piece, although it is unlikely.

The concept with the steel tube will be used to hold the Continental transition piece in place.

4.5.1.8 Redesigned concept

The redesigned concept can be seen in Figure 31, the structure is over four meters long. The bottom part is presented to the left in the picture. To the right is an arbitrary section of the structure. The sequence with two spacer holder levels and one corner connector level is repetitive throughout the structure (above the bottom plate holder).

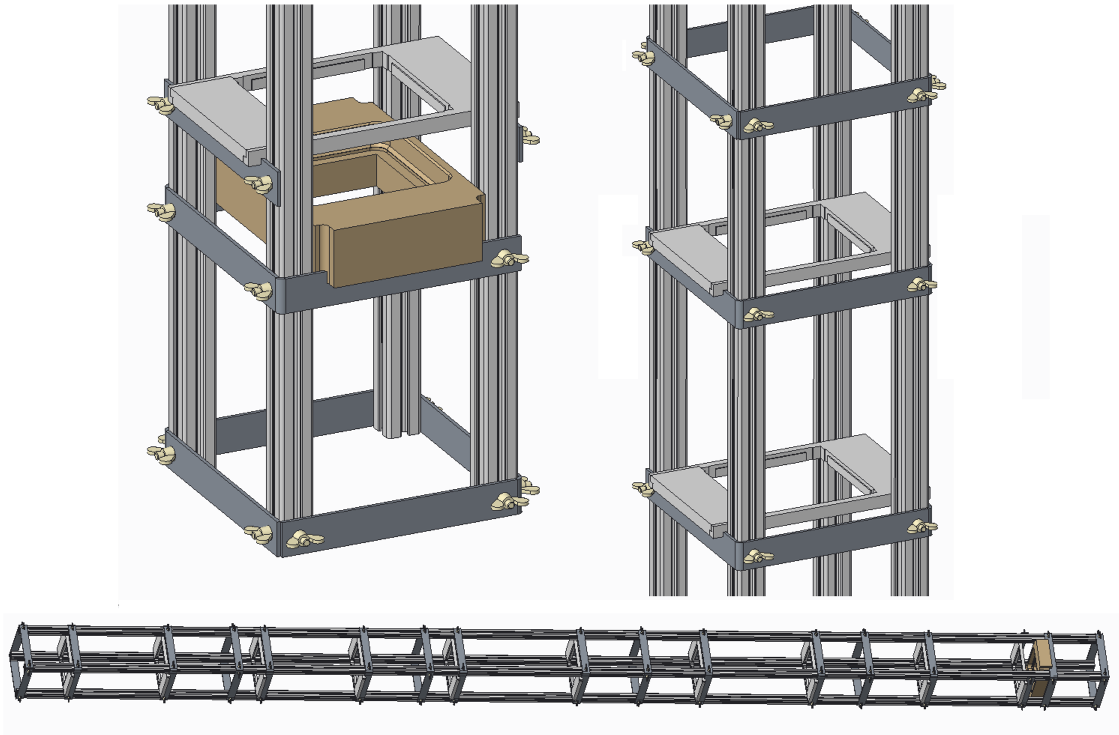


Figure 31 The redesigned concept

The assembly of the fixture is done by first fastening the screws and nuts to the level adjustment frames and frame connectors. These are then fastened to the fixture frame by fitting the screw head to the channel. The part is then slid up to the defined position where the screws are tightened to lock it in place.

The materials that are used in the structure are stainless steel, aluminum and POM.

The Continental transition piece is held in place by the holder presented in Figure 29. When inserting the transition piece and holder to the structure the bottom plate level needs to be lifted. That is done by assembling the handle and lifting the whole fuel bundle. Once the bottom plate is fastened to the transition piece the channel is lowered in to position.

4.6 Final design changes

The redesigned concept was presented at a second engineering review at the fuel laboratory. The concept was approved with only some minor changes.

From the engineering review it was decided to change the screw & nut configuration. Instead of having the screw on the inside of the profile and the nut on the outside it was decided to have the nut on the inside and the screw on the outside. To do so the wing nuts needed to be replaced by a nut that would fit inside the profile. It was found that a T-slot nut by AluFlex AB could be used if the dimensions of the profile were increased. By changing the dimensions of the profile the other components needed to be readjusted.

By consulting the supervisor Söderberg it was decided to redesign the spacer holder to increase the support given to the spacers.

The bottom plate holder was simplified to decrease the manufacturing cost.

The components used in the final design are presented in the following chapters.

4.6.1.1 Fixture frame

The dimensions of the profile were increased to fit the nut inside. Otherwise the concept remained unchanged. The new dimensions of the profile can be seen in Figure 32.

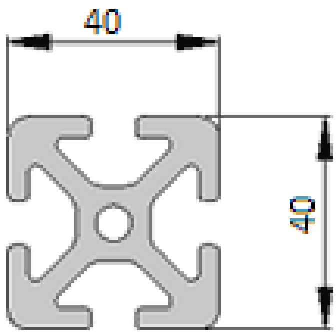


Figure 32 Increased dimensions of the profile (AluFlex AB)

4.6.1.2 Frame connector

The frame connectors were adjusted in length to fit the new dimensions of the frame, otherwise the concept remained unchanged. The part can be seen in Figure 24 that was presented earlier.

4.6.1.3 Level adjustment

The length of the level adjustment plates was adjusted to fit the new dimensions of the frame. Otherwise the concept remained unchanged and can be seen in Figure 26 and Figure 27.

4.6.1.4 Spacer holder

The spacer holder was redesigned to increase the support at the bottom of the spacers. This was done by adding teeth to the bottom of the holder. The length of the holder was increased to fit the level adjustment frame. The end plate of the spacer holder was also redesigned to fit the spacer holder. Two screws were added on the sides of the end plate to avoid the plate from lifting when the loads are applied. The final design can be seen in Figure 33 and the assembly can be seen in Figure 34. The spacer holder should be made in stainless steel.

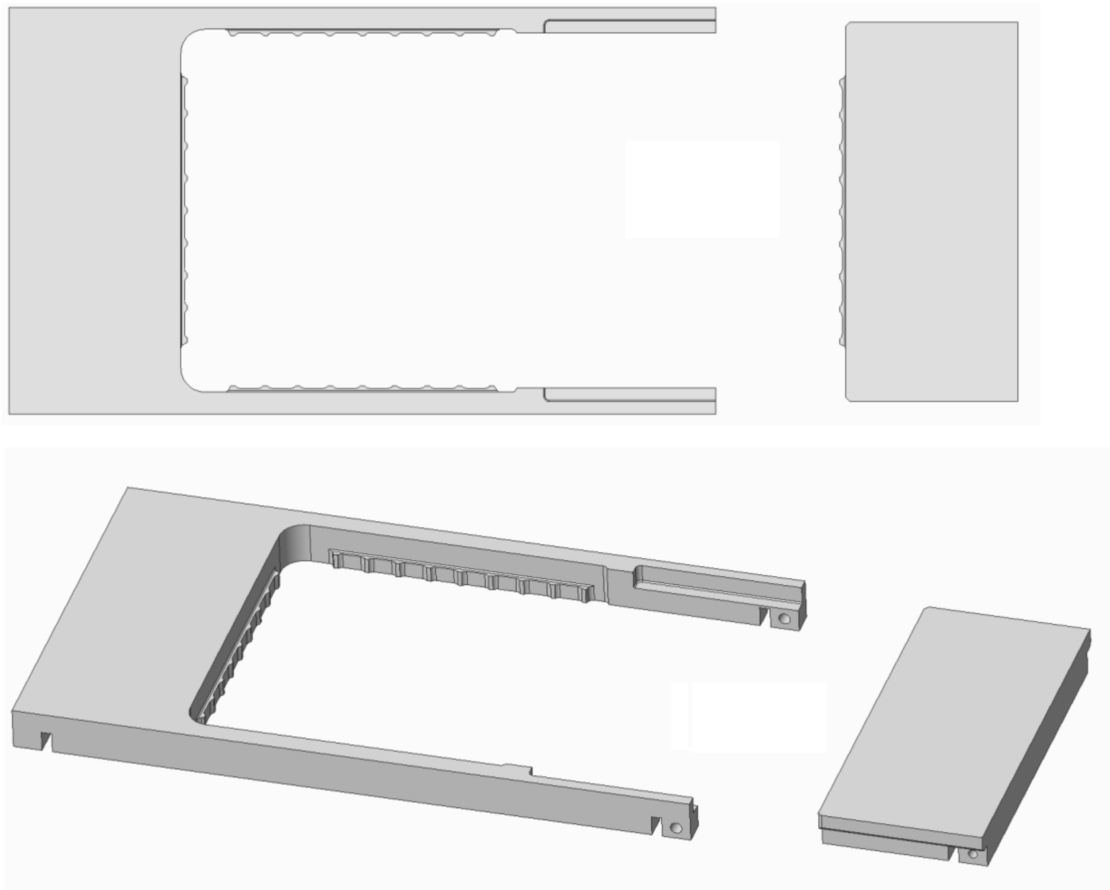


Figure 33 The final design with the spacer holder to the left and the end plate to the right.

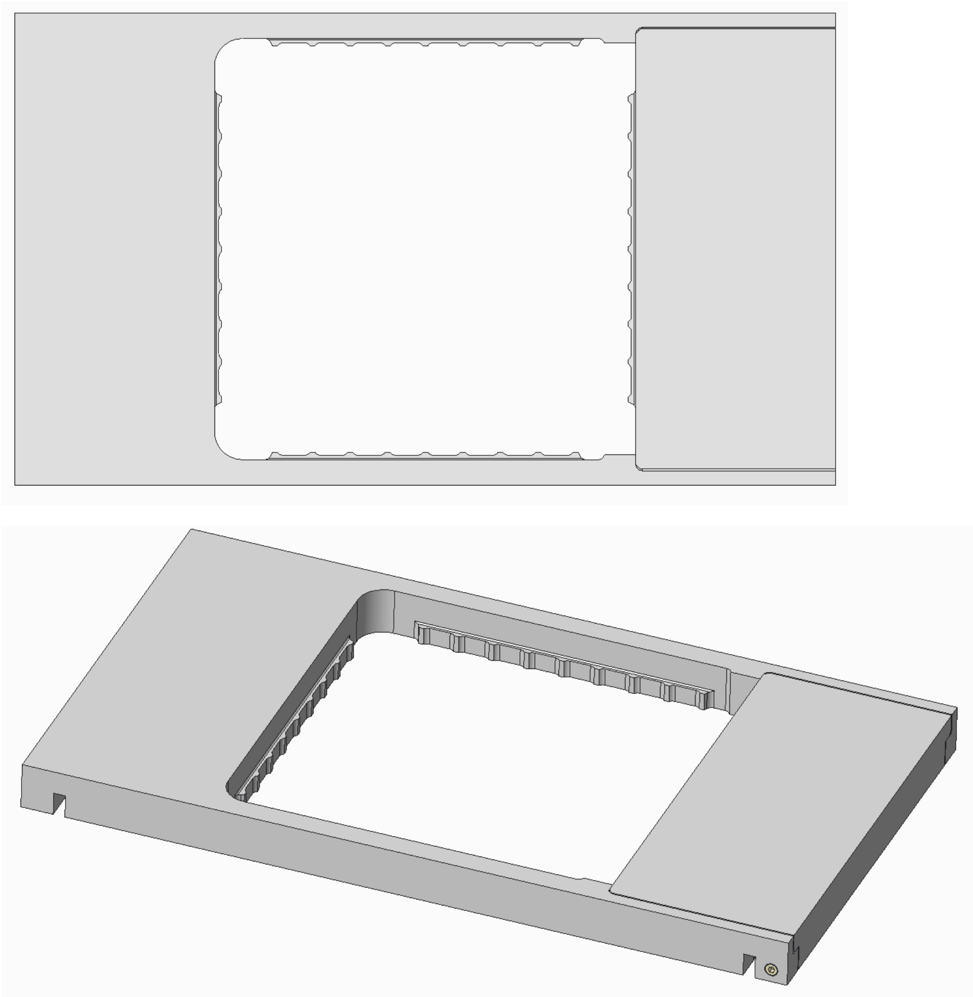


Figure 34 The final design of the assembled spacer holder.

4.6.1.5 Bottom plate holder

The bottom plate holder was simplified to reduce the cost of the part. Since the wing nuts are no longer used the corners do not have to be removed. The cross section was simplified so that it only follows the outer contours of the bottom plate. The component can be seen in Figure 35.

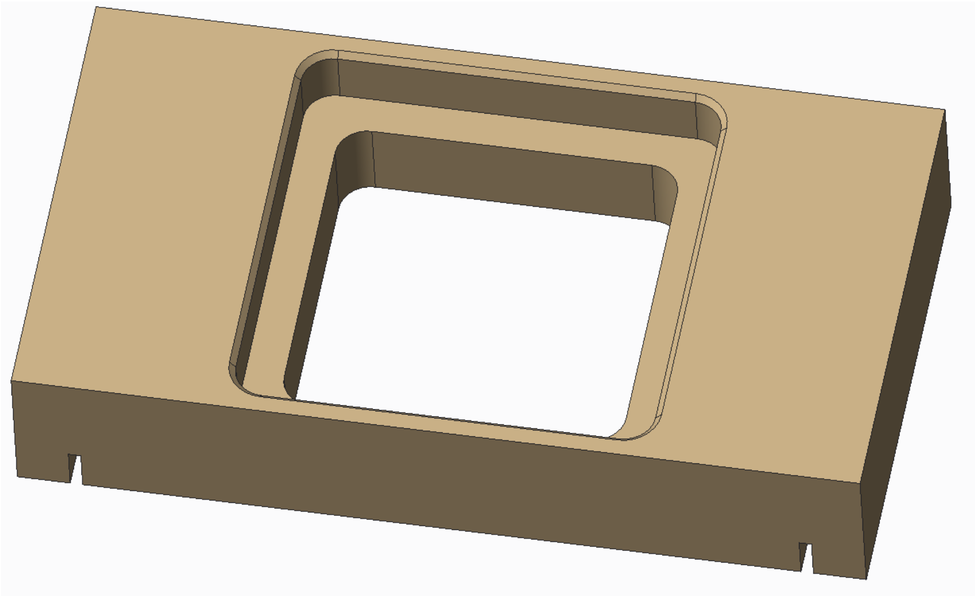


Figure 35 The final design of the bottom plate holder

4.6.1.6 Screws and nuts

The type of the screws is changed to fully threaded hexagon socket head cap screws according to ISO4762. The dimension of the screws is still M6 since this is the largest dimension that can be fitted inside the profile.

The nuts that are used are T-slot nuts by AluFlex AB that are placed inside the profile. A simplified presentation of the screws and nuts can be seen in Figure 36 and the screw joint can be seen in Figure 37 where part of the frame connectors can be seen.

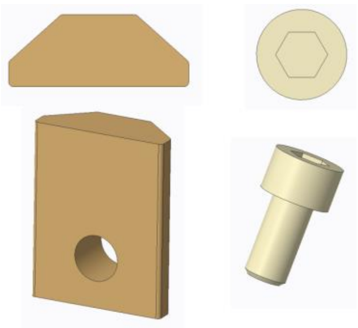


Figure 36 Simplified representation of the screws and nuts that are used in the final design.

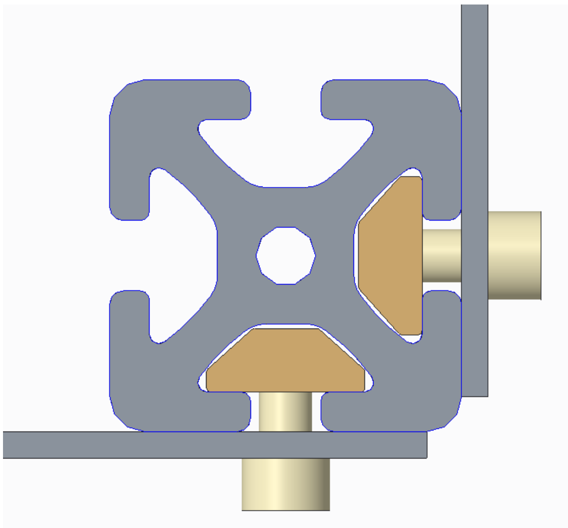


Figure 37 Screw joint holding the frame connectors in place.

4.6.2 **Final design**

The final design consists of ten levels of spacer holders, six levels of frame connectors and one level for the bottom plate holder. The bottom part and an arbitrary section of the structure can be seen in Figure 38. The sequence with two spacer holder levels and one frame connector level is repetitive throughout the structure (above the bottom plate holder). The structure is over 4 meters long and can be seen in Figure 39 where it is compared to a male with the length of 1.75 meters.

The assembly of the fixture is done by first fastening the screws and nuts to the level adjustment frames and frame connectors. These are then fastened to the fixture frame by fitting the T-slot nut to the channel. The part is then slid up to the desired position where the screws are tightened to lock it in place. The bottom plate holder and spacer holders are then placed on top of the level adjustment frames.

The materials that are used in the structure are stainless steel, aluminum and POM.

The Continental transition piece is held in place by the holder presented in Figure 29. When inserting the transition piece and holder to the structure the bottom plate level needs to be lifted. That is done by assembling the handle and lifting the whole fuel bundle. Once the bottom plate is fastened to the transition piece the channel is lowered in to position.

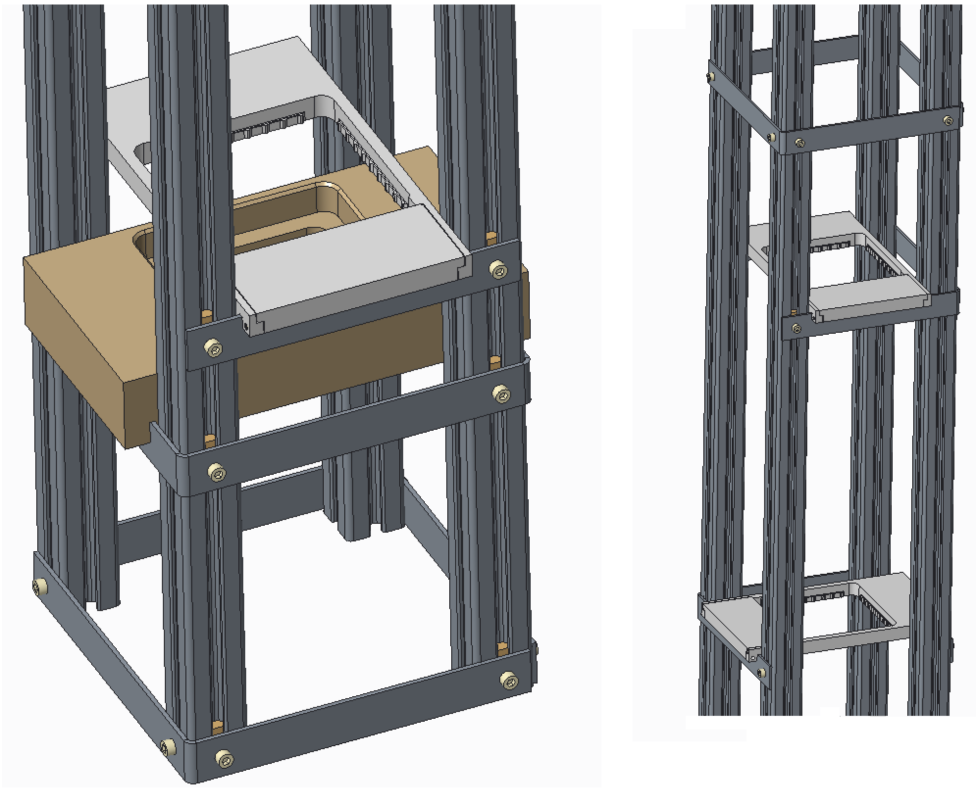


Figure 38 Final design of the assembly fixture.

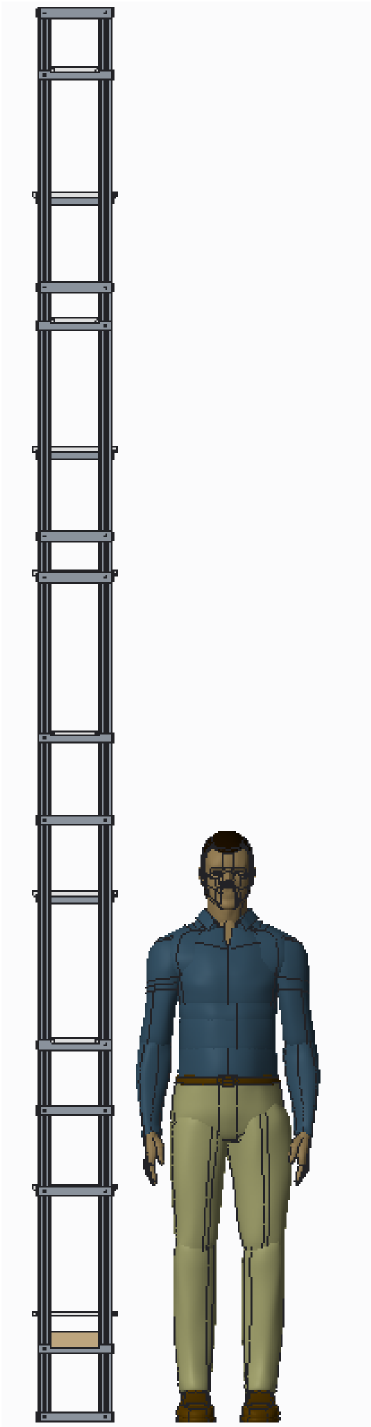


Figure 39 Final design of the assembly fixture compared to a male with the length of 1.74 meters.

5 Conclusions & Discussion

The results and assumptions from the project are discussed in the following chapters.

5.1 Endurance test program

The test program developed in this project could not be fully presented in the report due to confidentiality.

The test specifications derived in the test program are supposed to test the limits of the structure. But the tests must also reflect reality which means that they cannot be too tough. For example, the grid-to-rod gap in the spacers cannot be too large since that would not pass the inspection and the spacer would not be used.

The test specifications that are derived are considered to be reasonable and to be representative for the conditions that could occur in the reactor. Some of the specifications were reused from previous test programs. The other specifications were thoroughly discussed with the supervisor Söderberg to ensure that they were reasonable.

Some of the components used in the scoping test are modified since the test fuel rods are a bit longer than the Nordic ones. The channel is adjusted in length to fit the longer fuel rods as well as the water rods. The water rods are simplified by removing the bulges. None of these modifications should affect the test results substantially.

The test loop should be properly cleaned before the test. If any debris would come in to the system it could damage the components and ruin the entire test. For example if a rust flake would get stuck on a spacer it could start to fret on the fuel rod. It could be hard to tell if the fretting is from the grid-to-rod interaction or from debris when examining the rods after the test.

The test loop conditions that are used have not been modified since they have been established earlier to represent the conditions in the reactor. It should be mentioned that the test settings are measured at the inlet of the fuel assembly. This means that the conditions could deviate at the top of the fuel assembly. The effects of this will not be investigated further since it is not within the limits of this project.

5.2 Assembly fixture

The process of developing the assembly fixture partially followed the process described by Ulrich & Eppinger (2012). Many of the generated concepts are not presented in this report due to the fact that they could be eliminated on an early stage.

A visit to the fuel laboratory was made during the phase of understanding the problem. The requirements and functionality of the structure was discussed with the personnel who would use it, which lead to a deeper understanding of the problem. The currently used structure was studied at the same time. This affected the concept generation phase negatively since many of the ideas would become similar. It inhibited the free thought and it would have been better to first generate concepts and then study the current solution to make sure that all solutions are covered.

The final structure has a simple design to keep the cost down, but it is still easy to use and fulfills the requirements. The frame connectors and level adjustment frames are all designed with the same cross section. This was done to reduce the cost of the structure since only one dimension of the flat bar is needed.

The materials that are used in the structure are stainless steel, aluminum and POM. These materials do not rust which is desirable since the structure might be used for many years and could be exposed to moisture. The material selection eliminated some ideas on how to fasten the components. The frame is made in aluminum and the frame connectors are made in stainless steel. These two materials are not suitable to weld together.

The level adjustment frames are fastened with screws and T-nuts. The T-nut and the frame profile are both standard components from the same supplier. The screw joint solution makes it easy to change position of the frames which was requested in the specifications. A downside with this solution is that it greatly increases the number of components.

The assembly of the entire structure could be a bit tricky since there are a lot of parts that needs to be fitted to the aluminum frames. The length of the structure is over 4 meters long which makes it hard to handle. But since the structure only needs to be assembled one time this is acceptable.

If one of the adjustment frames or frame connectors needs to be replaced all the components under/above must be removed. This makes the structure harder to repair.

The forces acting on the frames are small, roughly 500 N, since the fuel rods are assembled one by one. It is the level adjustment frame that holds the bottom plate holder that is subjected to the highest forces. This frame needs to hold the entire weight of the structure which is around 280kg. To check that the screw joint can hold that weight a rough estimation has been done in appendix A. From the calculations in Appendix A it can be said that screws of dimension M6 should be enough.

A new requirement was introduced after the first engineering review. This was that for the Continental design the channel should be able to be assembled inside the fixture. The fixture did not need to be modified to fulfill this requirement since there was enough space for the channel to fit inside. A new component was needed to hold the transition piece in order to fasten the channel to the bottom plate. This was solved by using a short tube to keep the cost down.

Overall the structure fulfills the requirements and specifications given by the users at the fuel laboratory.

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Appendix A Screw Joint Calculations

A rough estimation of the strength in the screw joint for the bottom plate holder is presented in the following chapters. The calculations are based on the methods presented in the compendium "Skruvförband" by Åke Burman and Håkan Neveryd. The calculations have not been performed on the final design, but since the changes in the final design are small compared to the calculated design the calculations should be valid.

A.1 Load Case

The load is applied to the bottom plate holder and the holder is mounted on the U-frame. The U-frame is fastened to the fixture with four M6x20 screws. The assembly can be seen in Figure 40.

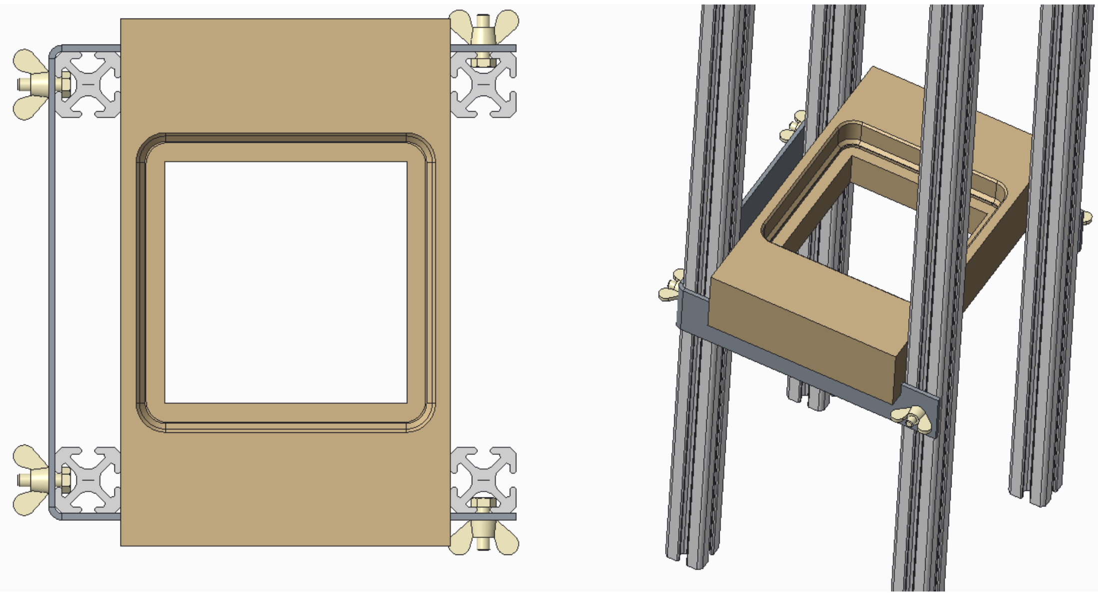

Figure 40 Assembly of the bottom plate holder

The applied load is 280 kg which represents the weight of the fuel bundle. The load is assumed to be equally distributed on the four screws. This means that each screw is loaded with

$$\frac{280*9.81}{4} \approx 687N \quad \text{(A.1)}$$

in the radial direction. The axial force that is needed to hold the screw in place with friction forces can be derived from Figure 41.

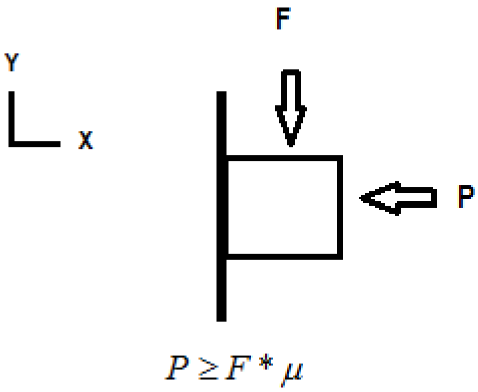

Figure 41 Derivation of frictional forces

μ is the static coefficient of friction between the two contact surfaces. This value is 0.61 for dry and clean aluminum to steel (Wikipedia). Solving the equation gives $P \geq 419.1N$ which would be the minimum requireded pretention. The equation does not consider embedment or the deviations from the assembly method. Therefore will the recommended torque acording to BUFAB be used instead, $M = 9.8Nm$ (BUFAB) which can be recalculated to pretension with the equation below.

$$M = F_S(0.16P + 0.58\mu_G * d_2 + 0.5\mu_U d_m \quad \text{(3.6)}$$

Where $\mu_G = 0.15$ (Skruvförband) and $\mu_U = 0.61$ (Wikipedia). P, d_2 and d_m are presented in Table 10 in the following chapeter. Inserting the given values and solving for F_S gives

$$F_S \approx 3306N$$

A.2 Screw stiffness

Table 10 Screw data

M6x20 ISO4017	
Pitch, P	1 mm
Outer diameter, d	6 mm
Inner diameter, d1	4.134 mm
Average diameter, d2	5.350 mm
Core diameter, d3	4.773 mm
Clearance holde, dh	6.6 mm
Load bearing outer diameter, dw	8.74 mm
Average contact diameter, dm	7.67 mm
Screw length, Ls	20 mm
Yield strength	640 Mpa
Tensile strength	800 Mpa
Youngs modulus, E	2,1e5 Mpa

The stiffness of the screw can be calculated by dividing the screw into three parts with different stiffness and then summarize them. These parts are as follows

Screw head

$$\omega_{sk} = \frac{0.5 * d}{E_S * A_N} \tag{3.20}$$

Where

$$A_N = \frac{\pi * d^2}{4}$$

Threaded part of the screw

$$\omega_{sg} = \frac{L_S}{E_S * A_{d3}} \tag{3.23}$$

Where

$$A_{d3} = \frac{\pi * d3^2}{4}$$

Part of screw in nut

$$\omega_{GM} = \frac{0.5 * d}{E_S * A_{d3}} + \frac{0.4 * d}{E_S * A_N} \tag{3.27}$$

The three parts are summirazed

$$\omega_S = \omega_{sk} + \omega_{sg} + \omega_{GM} \tag{3.19}$$

The total stiffness of the screw is given by

$$C_S = \frac{1}{\omega_S}$$

Inserting the values from Table 10 to the above mentioned equations gives

$$\omega_{sk} = 0.505 * 10^{-6} mm/N$$

$$\omega_{sg} = 0.532 * 10^{-6} mm/N$$

$$\omega_{GM} = 1.203 * 10^{-6} mm/N$$

$$\omega_s = 2.240 * 10^{-6} mm/N$$

The stiffness of the screw is

$$C_S = \frac{1}{\omega_S} = 446.4 kN/mm$$

A.3 Goods stiffness

The goods is the built up by the U-Frame and the aluminum profile. The total stiffness of the goods is given by adding the stiffness from of each part. The thickness of the U-frame is 3 mm and the Young’s modulus is 2,1e5 Mpa. The thickness of the aluminum profile is 3 mm and the Young’s modulus is 0.69e5 Mpa.

The stiffness for one part can be calculated with

$$\omega_G = \frac{L_K}{E_G * A_{ers}} \tag{3.24}$$

Where

$$A_{ers} = \frac{\pi}{4} * (d_w^2 - d_h^2) + \frac{\pi}{8} * d_w * L_K * ((x+1)^2 - 1) \tag{3.22}$$

Where

$$x = \sqrt[3]{\frac{L_K * d_w}{(L_K * d_w)^2}}$$

The total stiffness of the part is given by

$$C_G = \frac{1}{\omega_G}$$

A.3.1 Aluminum part

Inserting the values for the aluminum part to the equations mentioned above gives

$$x = 0.337$$

$$A_{ers} = 33.892 mm^2$$

$$\omega_{G,ALU} = 1.283 * 10^{-6} mm/N$$

A.3.2 Steel part

Inserting the values for the steel part to the equations mentioned above gives

$$x = 0.337$$

$$A_{ers} = 33.892 mm^2$$

$$\omega_{G,STEEL} = 0.422 * 10^{-6} mm/N$$

A.3.3 Total goods stiffness

$$C_G = \frac{1}{\omega_{G,ALU}} + \frac{1}{\omega_{G,STEEL}} = 3149.1 kN/mm$$

A.3.4 Stiffness check

The joint should be designed so that the goods are much stiffer then the screw. In practice should $\frac{C_G}{C_S}$ be at least 5. Inserting the calculated values gives

$$\frac{C_G}{C_S} = \frac{3149.1}{446.4} = 7.1$$

Which is ok.

A.3.5 Shortest distance between screws

The shortest distance between two screws or the edge of the goods is given by

$$D_A = d_w + L_K$$

For the calculated joint this distance is

$$D_A = 8.74 + 6 = 14.74 mm$$

A.4 Embedment

The pretension in a screw joint decreases over time due to embedment in the contact surfaces. The loss in pretension is given by

$$F_{FZ} = \frac{f_Z}{\omega_S + \omega_G} \tag{5.3}$$

Where

$$f_Z = Z_{Y1} + Z_{Y2} + Z_G \tag{5.4}$$

f_Z is depending on the surface roughness, tabulated values for the estimation of f_Z can be found on page 40 in "*Skruvförband"*.

For this calculation is the surface roughness estimated to $10\mu < R_Z > 40\mu$ because it reflects normal manufacturing. The load type is shear forces. This gives

$Z_{Y1} = 2*4.5 = 9\mu m$

$Z_{Y2} = 2.5\mu m$

$Z_G = 3\mu m$

$f_Z = 9 + 2.5 + 3 = 14.5\mu m$

The loss in pretension is then

$$F_{FZ} = \frac{14.5*10^{-3}}{2.240*10^{-6} + 1.705*10^{-6}} \frac{mm}{mm/N} = 3.676kN$$

A.5 Assembly method

Some of the most common assembly methods for screw joints are listed on page 44 in *"Skruvförband"*. The moment needed to give the screw the decided pretension will vary different depending on which assembly method that is used. The tightening factor α_M is defined as

$$\alpha_M = \frac{F_{F_{\max}}}{F_{F_{\min}}} \qquad (5.6)$$

Where

$F_{F_{\max}}$ = Maximum pretension

$F_{F_{mijn}}$ = Minimum pretension

The assembly method for the used screw joint is by hand force. This is not among the common assembly methods listed in *"Skruvförband"*. α_M is therefore estimated to the highest value listed, which is 4.

$\alpha_M = 4$

A.6 Dimensioning screw forces

The dimensioning screw forces are given by

$$F_{S_{\max}} = F_{F_{\max}} + F_{LS} - F_{FZ} \tag{5.10}$$

Where $F_{F_{\max}}$ is given by

$$F_{F_{\max}} = F_{F_{medel}} * \frac{2\alpha_M}{1+\alpha_M} \tag{5.9}$$

Where $F_{F_{medel}}$ is given by

$$F_{F_{medel}} = F_{F_{\min}} * \frac{1+\alpha_M}{2} \tag{5.7}$$

$F_{F_{\min}}$ is the smallest force needed for the joint to work as a friction joint. This was calculated in chapter A.1 and was denoted F_S, $F_S = F_{F_{\min}} = 3306N$. F_{LS} is given by

$$F_{LS} = F_L \eta \frac{\frac{1}{C_G}}{\frac{1}{C_S} + \frac{1}{C_G}} \tag{4.39}$$

Where η is a factor depending on where the force is acting. For most constructions is $\eta = 0.5$ (Skruvförband). Solving equations (4.39), (5.7), (5.9) and (5.10) gives

$$F_{LS} \approx 205N$$

$$F_{F_{medel}} = 8265N$$

$$F_{F_{\max}} = 13224N$$

$$F_{S_{\max}} = 13224 + 205 - 3676 = 9753N$$

A.7 Controlling tensions in the screw

To control that the screw will not break from the applied loads Von Mises yield criterion is used.

$$\sigma_e = \sqrt{\sigma^2 + 3\tau^2}$$

The equation can be rewritten as

$$\sigma_e = \sqrt{(\frac{F_S}{A_S})^2 + 12\pi \frac{M_G^2}{A_S^3}} \quad (6.8)$$

Where

$$A_S = \frac{\pi}{4}(\frac{d_2 + d_3}{2})^2$$

And

$$M_G^2 = F_S(0.16P + 0.58\mu_G d_m)$$

Inserting the given values, $F_S = F_{S_{max}}$, and solving the equations gives

$$M_G^2 \approx 2068Nmm$$

$$A_S = 20.1mm^2$$

$$\sigma_e \approx 505.3N/mm^2$$

The screw holds if $\sigma_{e_{max}} \geq \sigma_e$.

$$640N/mm^2 \geq 505.3N/mm^2$$

A.8 Conclusions

Some approximations have been done during these calculations which could affect the results slightly. The friction coefficient between the aluminum and the steel parts has been set to 0.61, which is quite high. The coefficient should be between aluminum and stainless steel but that could not be found.

The surface roughness has been estimated to be around $10\mu < R_Z > 40\mu$ which is reasonable. The temperature effects are neglected since the structure will be assembled and used at the same place.

Although some approximations have been done the calculations show that screws with dimension M6 are enough to handle the weight of the fuel bundle.