# The novel Cryogenic Cooling and Cutting System (CCCS) for the decommissioning process of Offshore Monopile Foundations (OMFs)

Kenneth Bisgaard Christensen

# Scoop of the Project

**Development of a novel cutting tool based on the CCCS, with the aim of:**

- Internal cutting capability
- Reduce cutting time for OMFs
- Reduce decommissioning time - target around **20%**
- Reduce operational cost - target around **20%**
- Reduce environmental footprint ($CO_2$ equivalents) - target around **25%**

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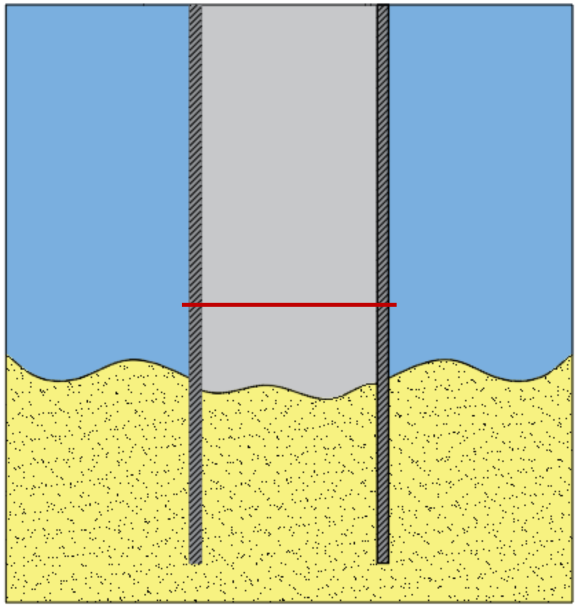
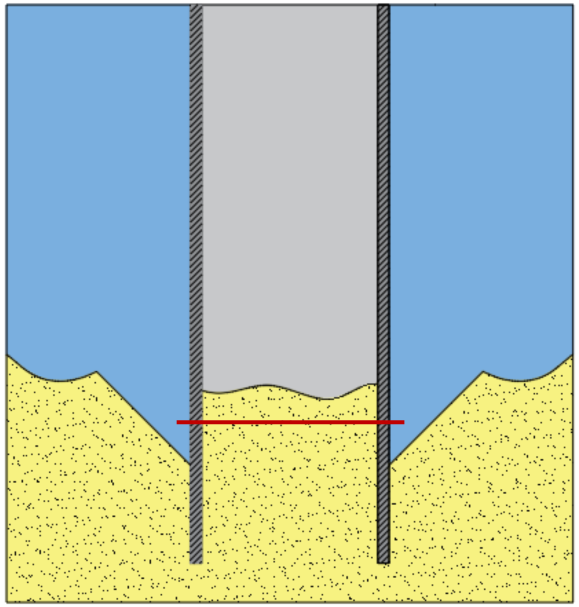
# Place of Cutting Operation

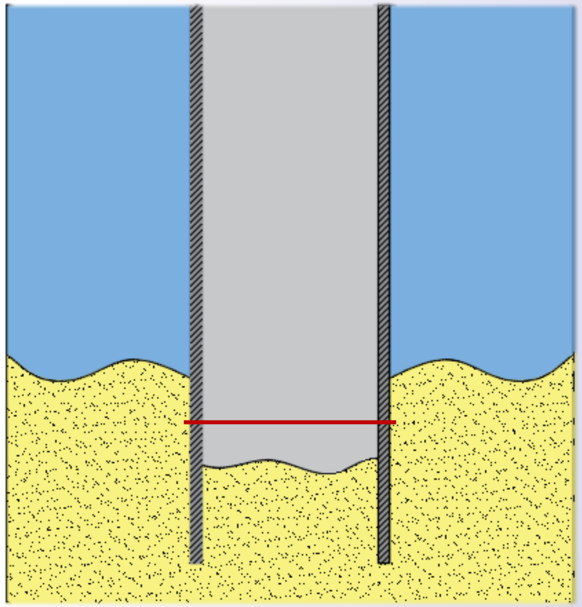
- Cutting options of foundations at or below the bedrock of the sea



Above mudline



External excavation



Internal excavation

# Overview of the Current Cutting Techniques

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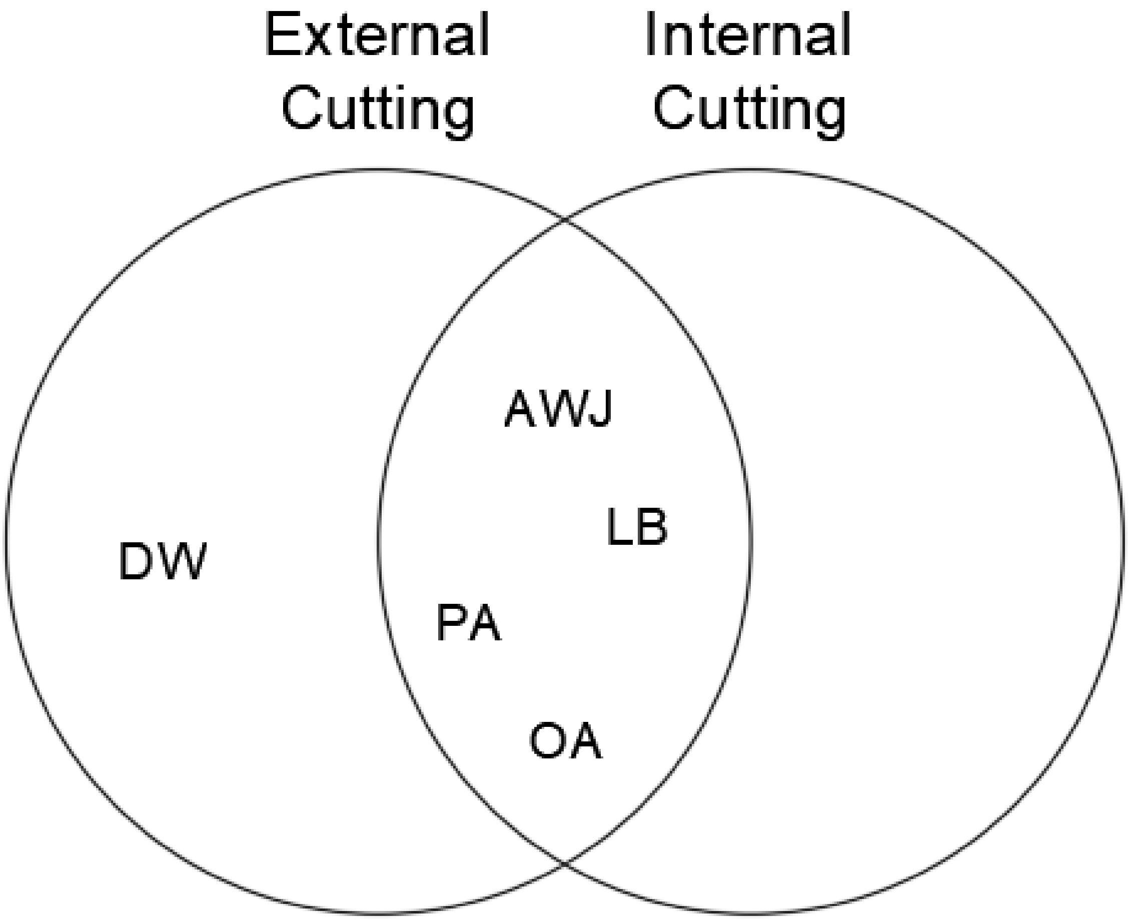


*Figure 1.* Venn diagram illustrating the applicability of different techniques for internal and external offshore cutting operations

# Comparisons of the Current Cutting Techniques

TABLE II. COMPARISON OF THE DIFFERENT CONVENTIONAL CUTTING TECHNIQUES EMPLOYED IN THE INDUSTRY BASED ON DIFFERENT PERFORMANCE MEASURES [13], [41], [42]

| Cutting Technique | DW | AWJ | OA | LB | PA |
|---|---|---|---|---|---|
| Type | External | External/Internal | External/Internal | External/Internal | External/Internal |
| Cost | High | Highest | Lowest | Medium | Low |
| Cutting Speed ($S_c$) | Low | Low | Medium | High | Highest |
| $w_t$ 12.7 mm (XS) | [1]50 mm/min | 950 mm/min | 500 mm/min | 1000 mm/min | 2200 mm/min |
| $w_t$ 25.4 mm (XXS) | [1]50 mm/min | 365 mm/min | 400 mm/min | 900 mm/min | 1100 mm/min |
| Productivity | Medium/low | Medium/ low | Low | Highest | High |
| Precision | High | Highest | Low | Medium | High |
| Quality | High | Highest | Low | Medium | low |
| Energy Consumption | Medium | High | Medium | High | Highest |
| Safety Risks | Small fragments and cuts | Small fragments, abrasive mud and cuts | Hazardous vapours, burns and gas explosions | Hazardous vapours, aerosol and burns | Hazardous vapours, dross and burns |
| Environmental Impact | Medium | Medium | Medium | Low | Low |
| Ambient Applicability | All | All | Non-Explosive | Non-Explosive | Non-Explosive |
| Material Applicability | All Steels | All Steels and Composites | All Steels, but mostly Carbon Steel | Non Reflective Steels | All Steels |
| Maximum $w_t$ | +300 mm | +300 mm | +300 mm | 60 mm | 50 mm |

[1]The DW cutting applies directional diameter cutting and not circumference cutting in other cutting techniques.


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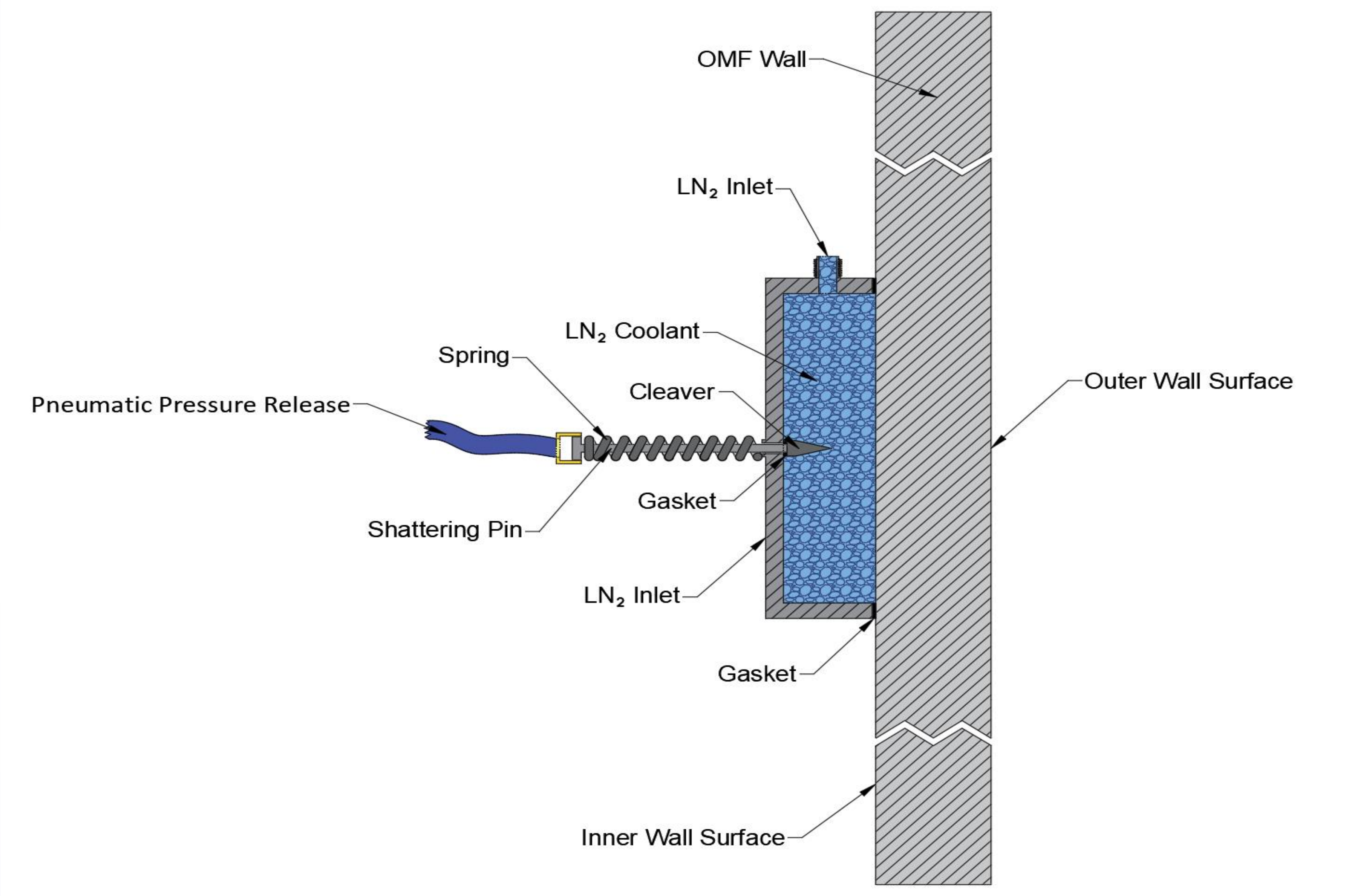
# Conceptual Design of the CCCS

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# Cryogenic Cooling and Cutting System (CCCS)

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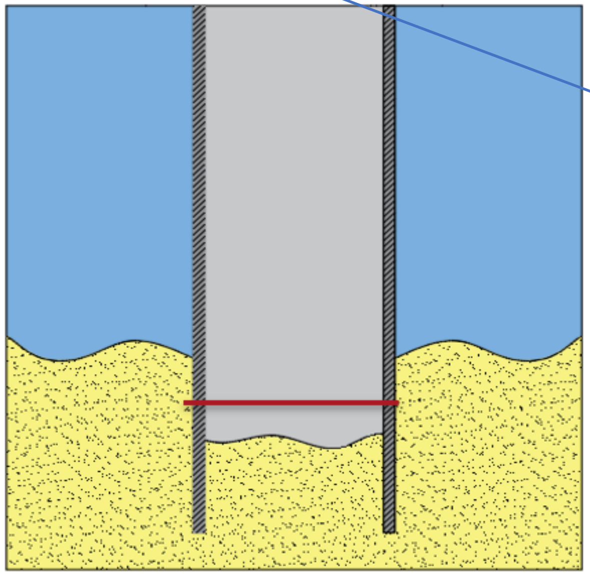
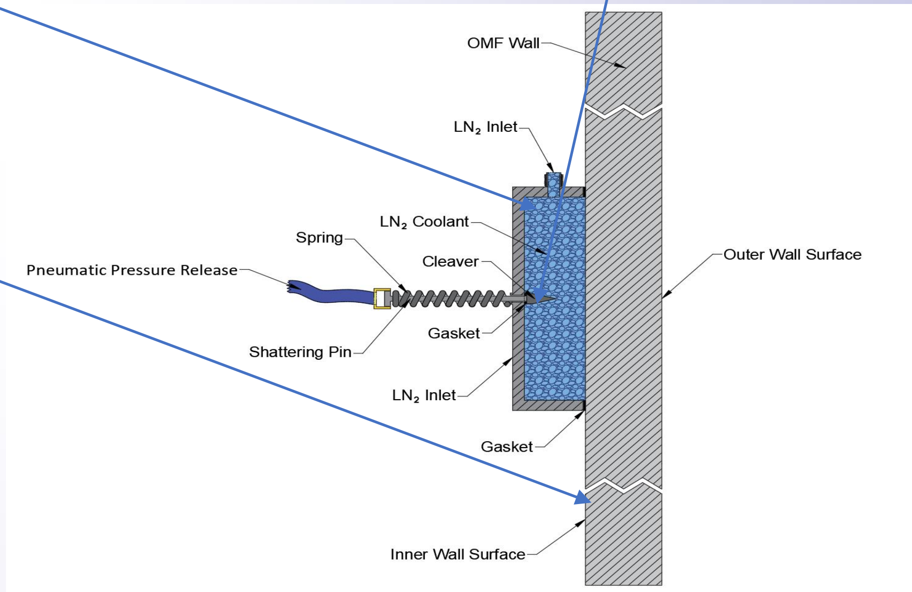
**Workpiece**

**Cryogenic Cooling System**

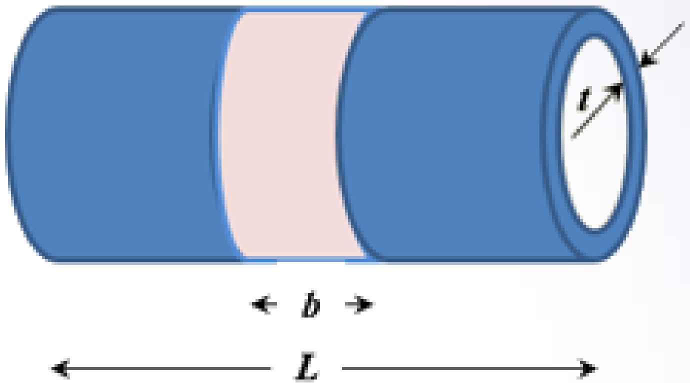
**Brittle Cutting System**



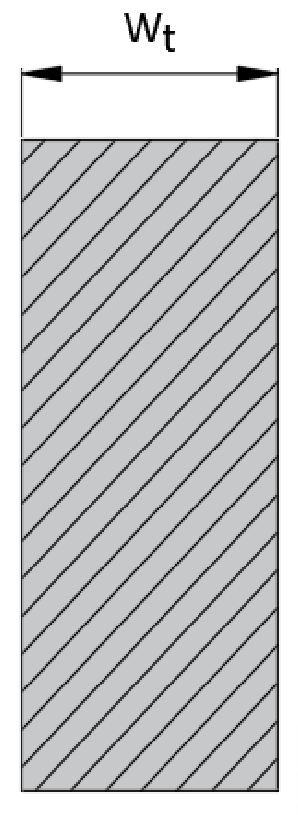
Internal Cutting Method



# Cooling Bandwidth Requirements




*Pipe wall (t) pipe lenght (L) width of cryogenic cooling aid (b).*

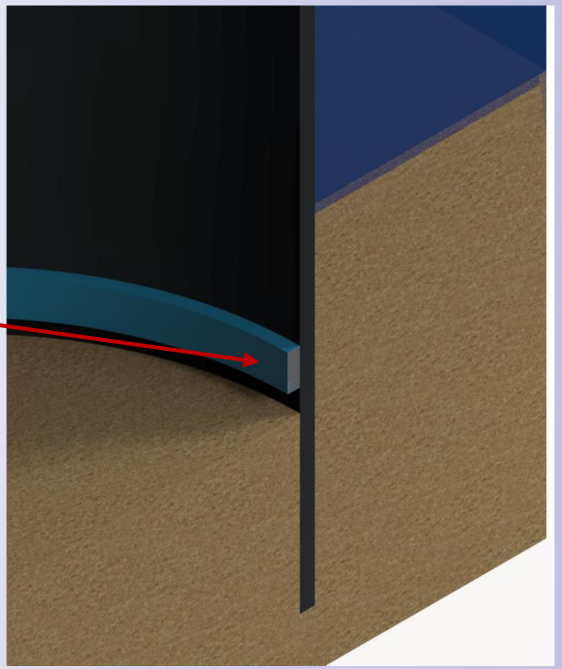



## Target for cooling time under 7200s (2 hours):

The cooling time dependents on:

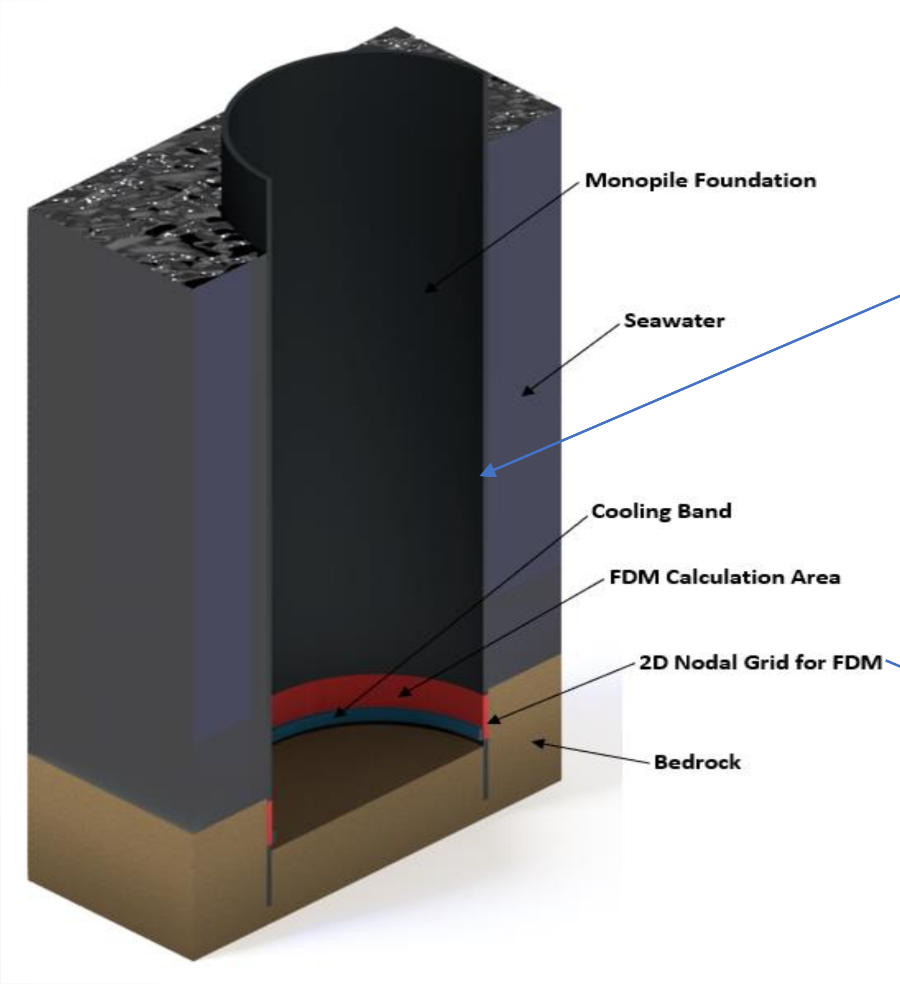
- The $W_t$ of the OMF
- The width of the cooling band
- Ambient conditions
- Steel type

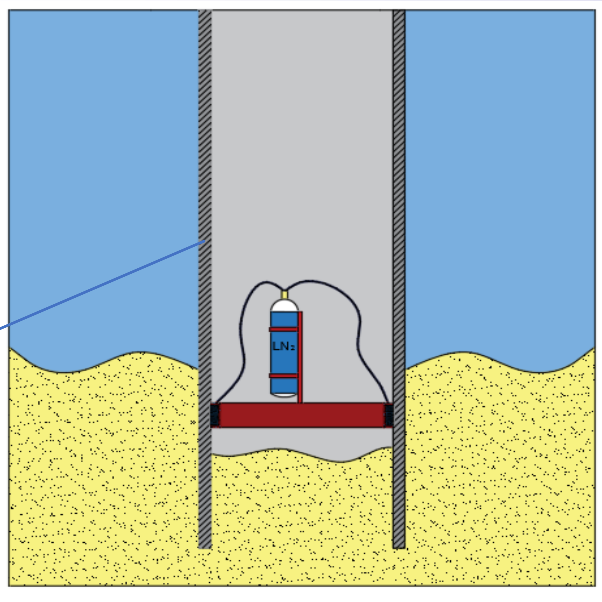
Cooling Band (b)

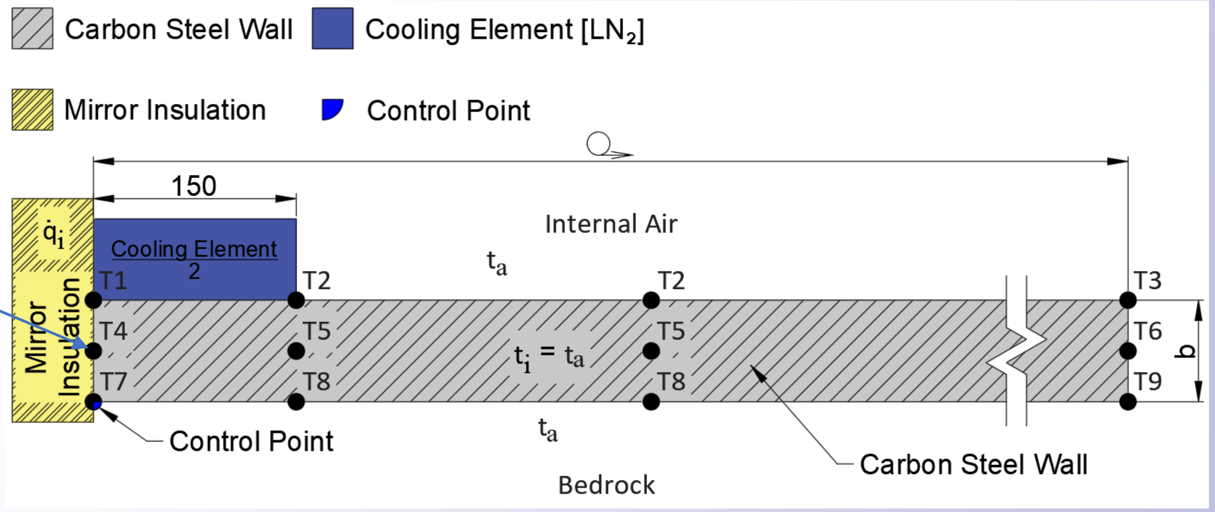


# Conceptual Design and Application of CCCS

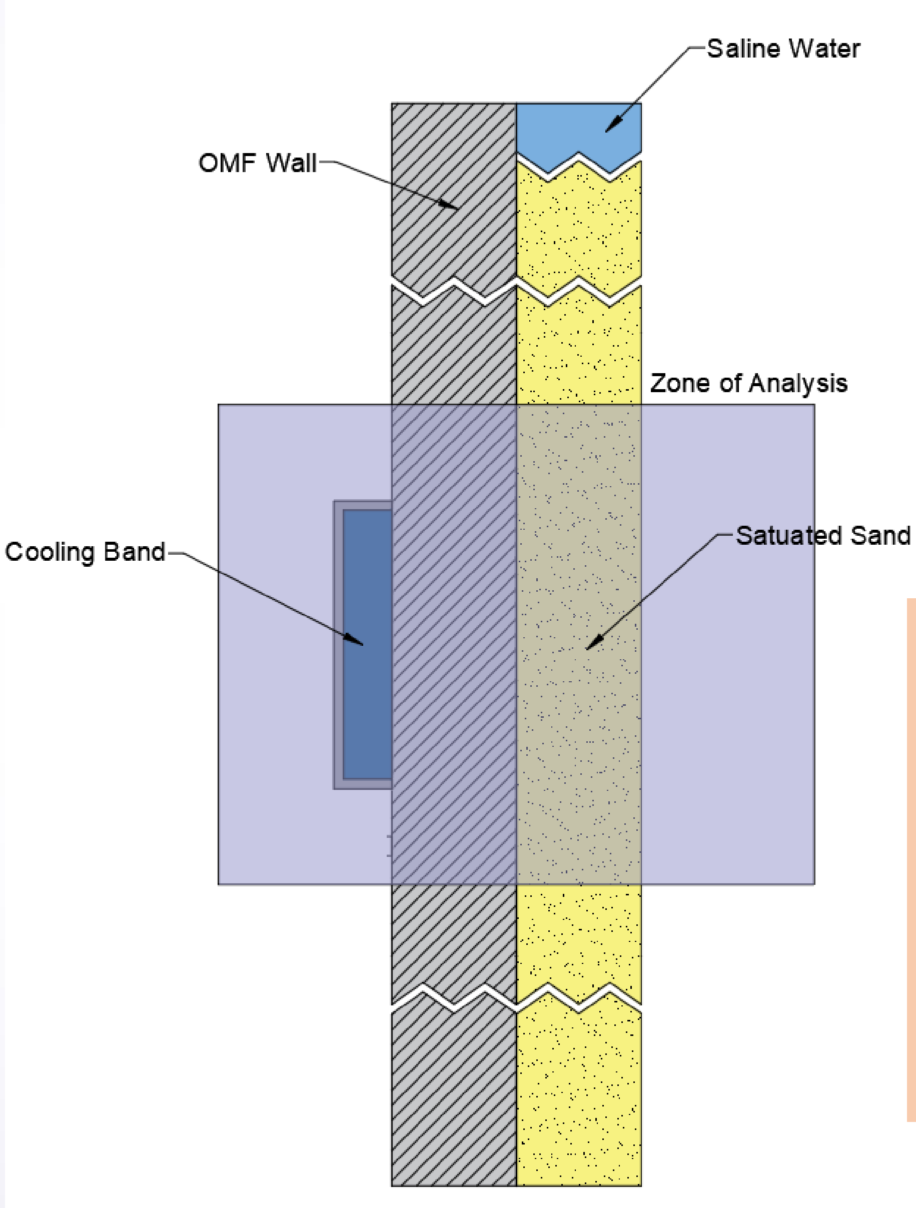
## Internal cutting:



# 2D Simulation Model and Data for the Finite Difference Transient Heat Transfer Model




**OMF Specifications:**

Wall Thickness [$W_t$]: **100 mm**

**Ambient Specifications:**

Saline Water Temperature [$t_a$]: **10 °C**
Heat Transfer Coefficient: **25 W/m²*K**

Saline Water Temperature [$t_w$]: **5 °C**
Heat Transfer Coefficient: **1500 W/m²*K**

Saturated Sand Temperature [$t_s$]: **5 °C**
Thermal Conductivity: **48 W/m*K**

**Liquid Nitrogen [LN2] Specifications:**

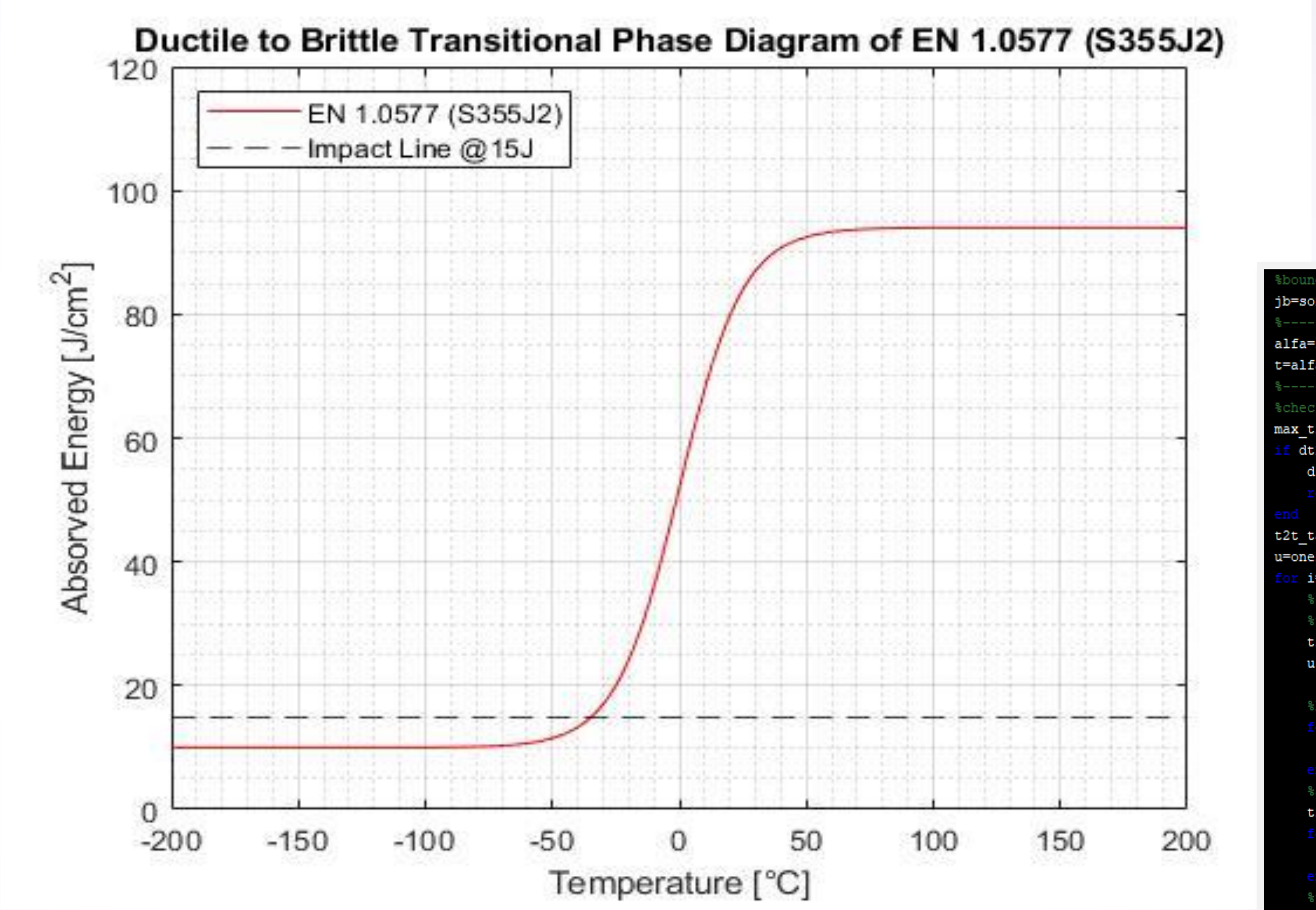
Temperature: **-196 °C**
Heat Transfer Coefficient: **120 W/m²*K**

**Carbon Steel Specifications:**

Type: **A355J2 / ISO EN 1.0456**

Thermal Conductivity: **48 W/m*K**
Density: **7850 kg/m³**
Specific Heat: **470 J/kg*K**

# Transient Heat Transfer Calculations

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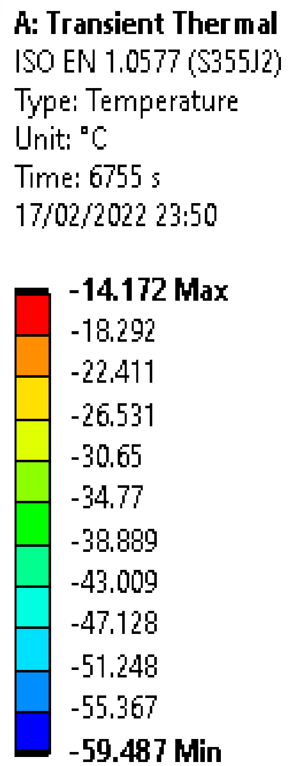
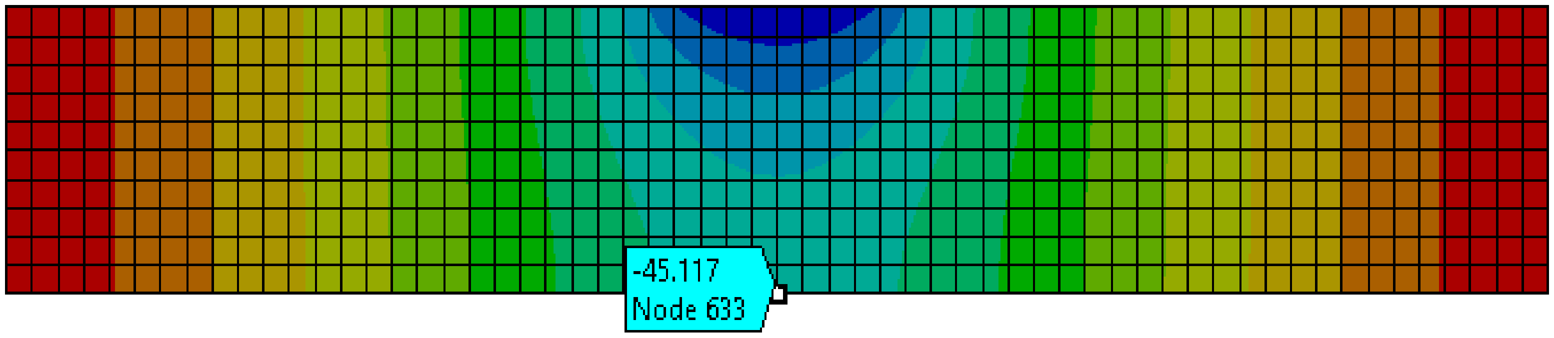
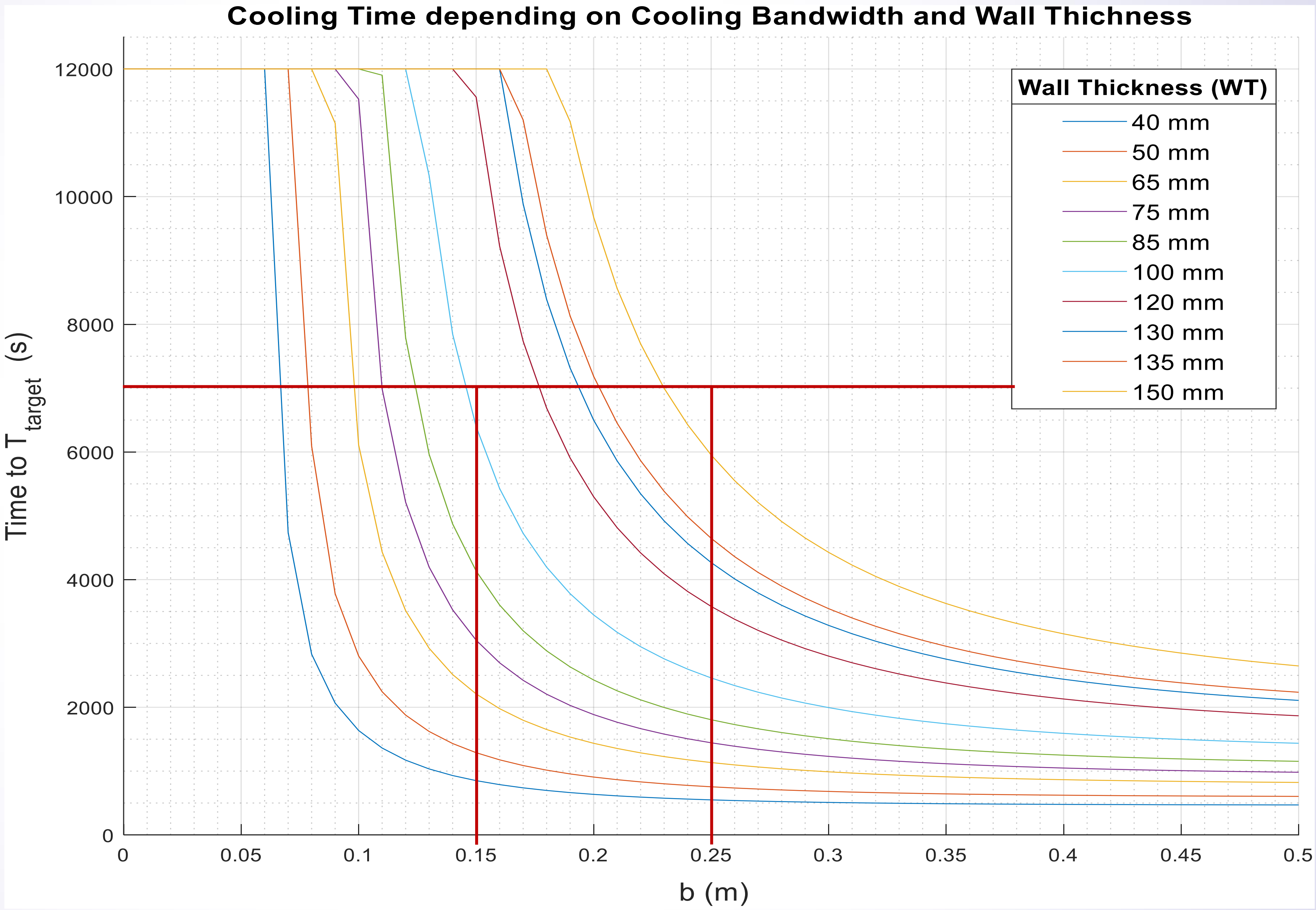
```
%boundary nodes
jb=sort([1,2:nl,nl+1:n-1,n,n+1:n:(m-2)*n+1,(m-1)*n+1,m*n,2*n:n:(m-1)*n,(m-1)*n+2:m*n-1]);
%-----------------------------------------------------------------------
alfa=k/dens/cp;%thermal diffusitivity (m^2/s)
t=alfa*dt/del^2;%dimensionless time
%-----------------------------------------------------------------------
%check for stability
max_time_step=del^2/4/alfa/(1+h_n*del/k);
if dt>=max_time_step
    disp(['Unstable! time step = ',num2str(dt), ' > max permissible time step =', num2str(max_time_step)])
    return
end
t2t_target=t_t;
u=ones(nt,m*n)*t_i;
for i=1:nt-1
    %-------------top surface
    %top left
    tinf=t_n;hlk=h_n*del/k;
    u(i+1,1)=(1-4*t-2*t*hlk)*u(i,1)+2*t*(u(i,2)+u(i,n+1)+hlk*tinf);

    %LN part except top left
    for j=2:nl
        u(i+1,j)=(1-4*t-2*t*hlk)*u(i,j)+t*(u(i,j-1)+u(i,j+1)+2*u(i,j+n)+2*hlk*tinf);
    end
    %air part except top right
    tinf=t_a;hlk=h_a*del/k;
    for j=nl+1:n-1
        u(i+1,j)=(1-4*t-2*t*hlk)*u(i,j)+t*(u(i,j-1)+u(i,j+1)+2*u(i,j+n)+2*hlk*tinf);
    end
    %top right
    u(i+1,n)=(1-4*t-4*t*hlk)*u(i,n)+2*t*(u(i,n-1)+u(i,2*n)+2*hlk*tinf);
    %--------------left surface
    for j=n+1:n:(m-2)*n+1%left surface except top left and bottom left
        u(i+1,j)=(1-4*t)*u(i,j)+t*(u(i,j-n)+2*u(i,j+1)+u(i,j+n));
    end
    j=(m-1)*n+1; % bottom left
    u(i+1,j)=(1-4*t-2*t*hlk)*u(i,j)+2*t*(u(i,j+1)+u(i,j-n)+hlk*tinf);
```

# Transient Heat Transfer Results




The cooling time to reach -45 °C in the fracturing point of the OMF Wall: **6577 Seconds**



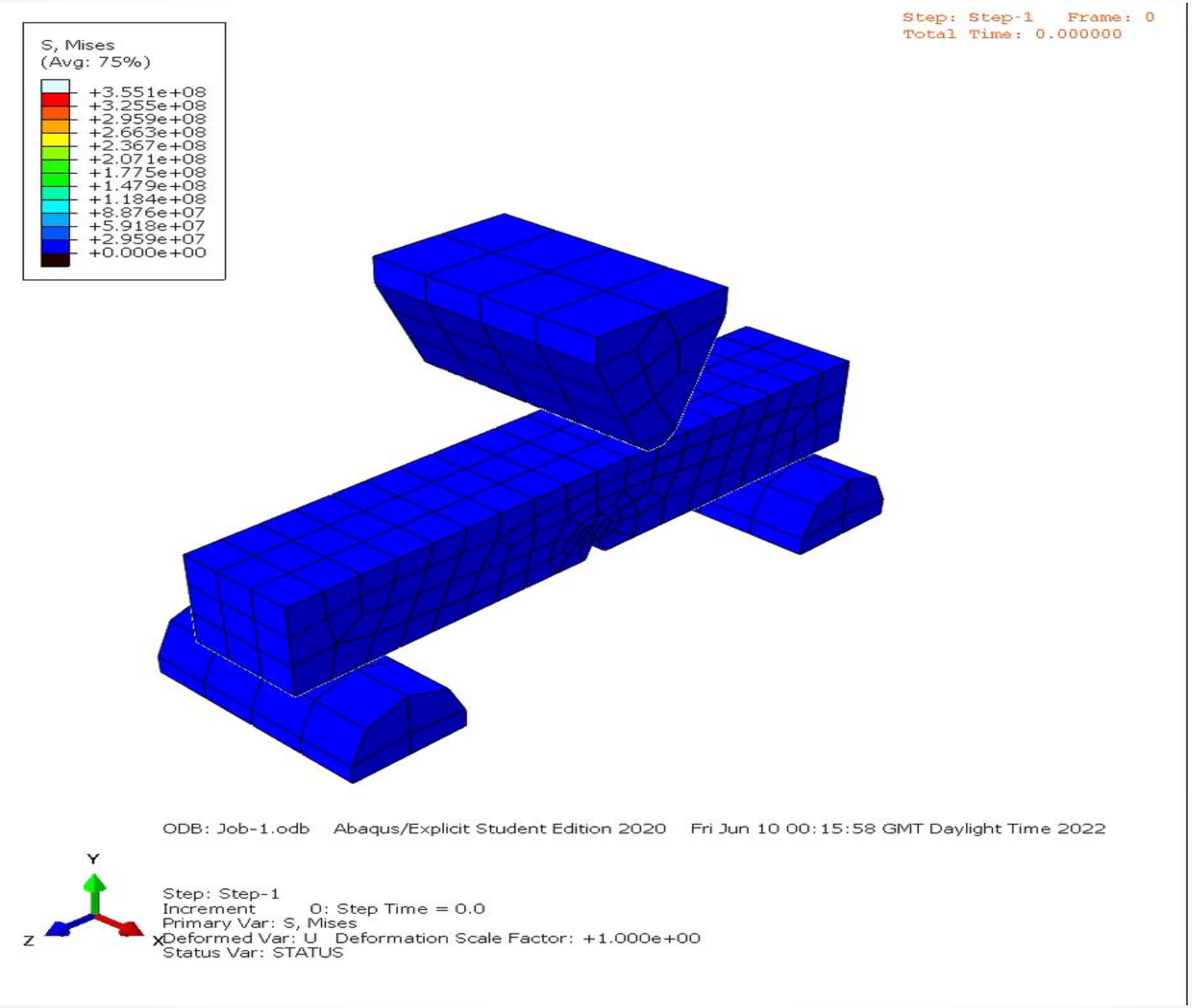

Bandwidth 150 mm:

- 40 – 100 mm

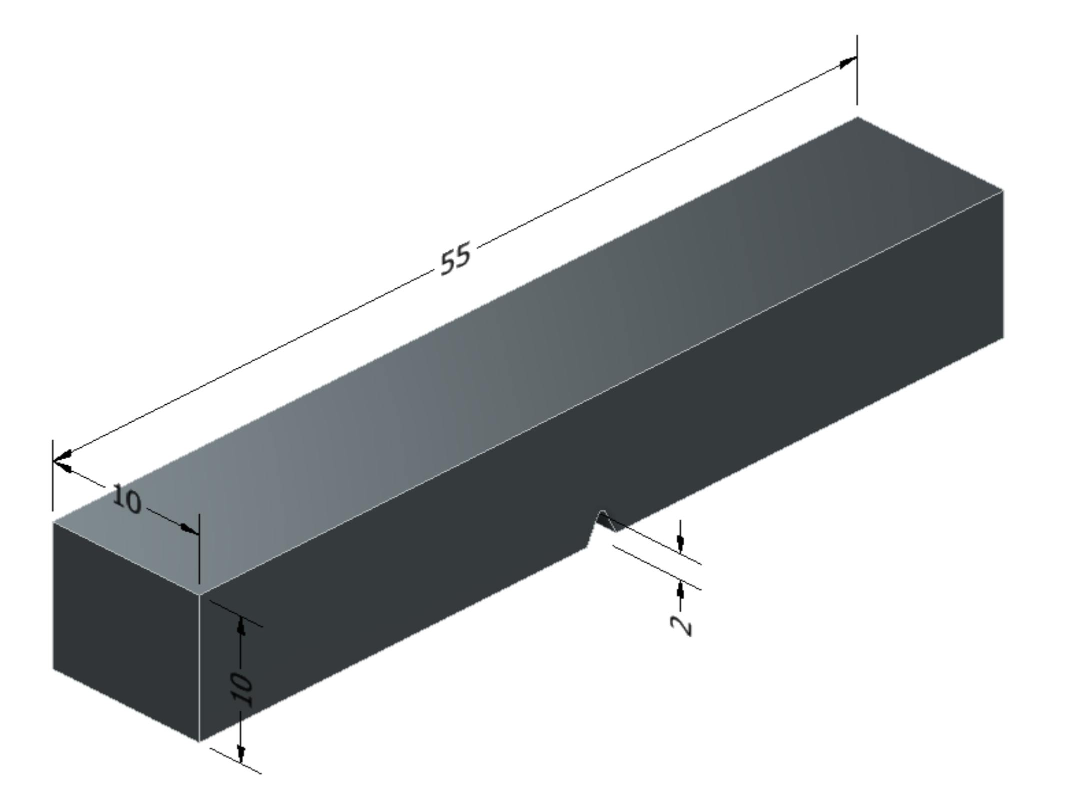
Bandwidth 250 mm:

- 105 – 150 mm

# Impact Energy Absorption and Fracturing Test



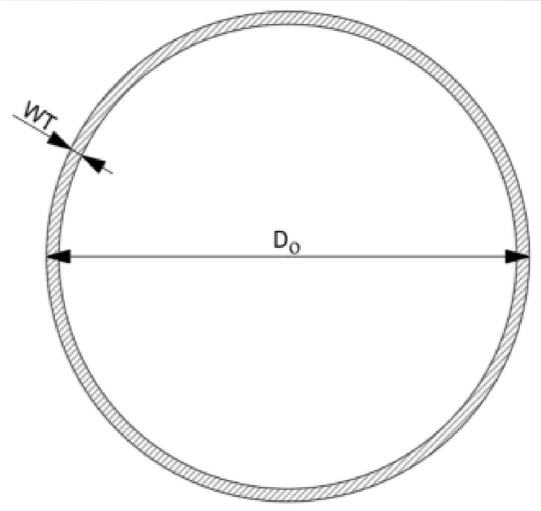

V-Notch



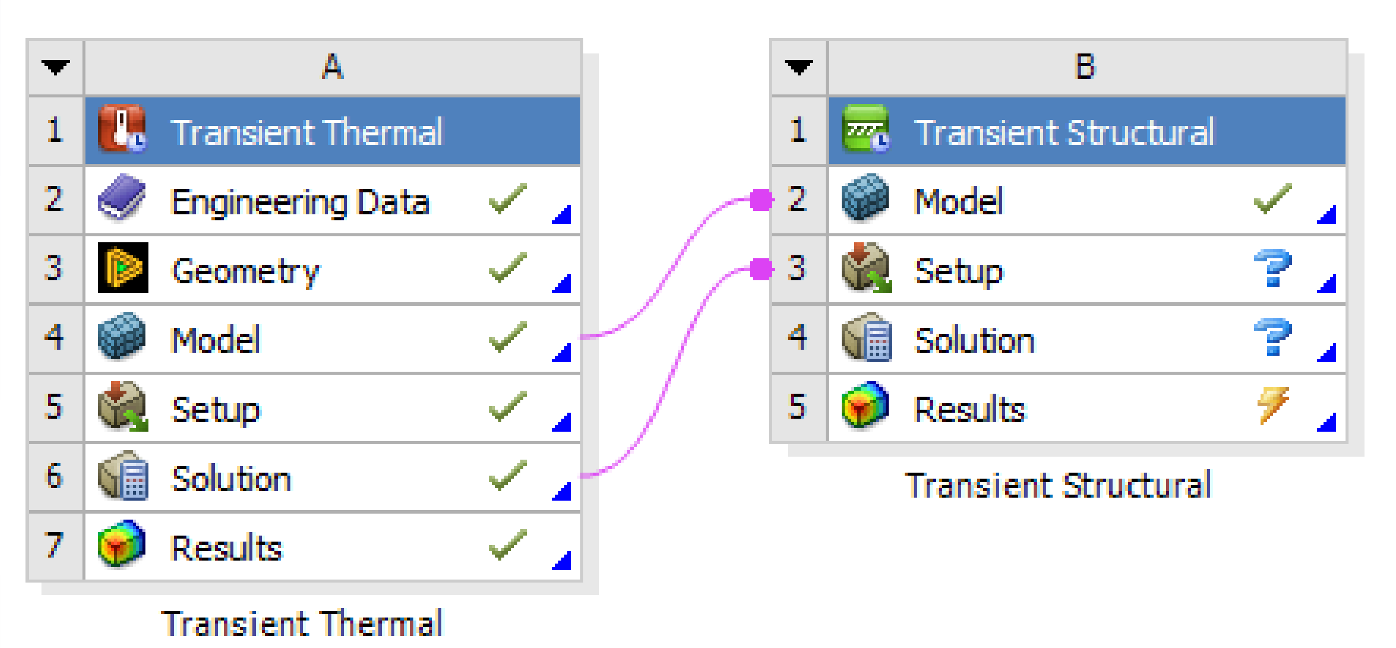
# Impact Energy Absorption ($E_i$) Requirements

Cryogenic cooling reduces the $E_i$ requirement for the shattering process of the carbon steel by 88%:

| Impact Energy Required (J) | | | | | |
|---|---|---|---|---|---|
| Diameter ($D_O$) mm | Thickness ($W_t$) mm | Steel Area $cm^2$ | Steel Temperature and $J/cm^2$ | | |
| | | | 20 °C | 0 °C | -45 °C |
| | | | 128 $J/cm^2$ | 80 $J/cm^2$ | 15 $J/cm^2$ |
| 2500 | 130 | 9679 | 1238912 | 774320 | 145185 |
| 3000 | 40 | 3720 | 476160 | 297600 | 55800 |
| 3400 | 50 | 5262 | 673536 | 420960 | 78930 |
| 3400 | 120 | 12365 | 1582720 | 989200 | 185475 |
| 4000 | 65 | 8035 | 1028480 | 642800 | 120525 |
| 7500 | 85 | 19801 | 2534528 | 1584080 | 297015 |
| 8000 | 135 | 33357 | 4269696 | 2668560 | 500355 |
| 10000 | 150 | 46417 | 5941376 | 3713360 | 696255 |



# Transient Heat Transfer Data Transfer



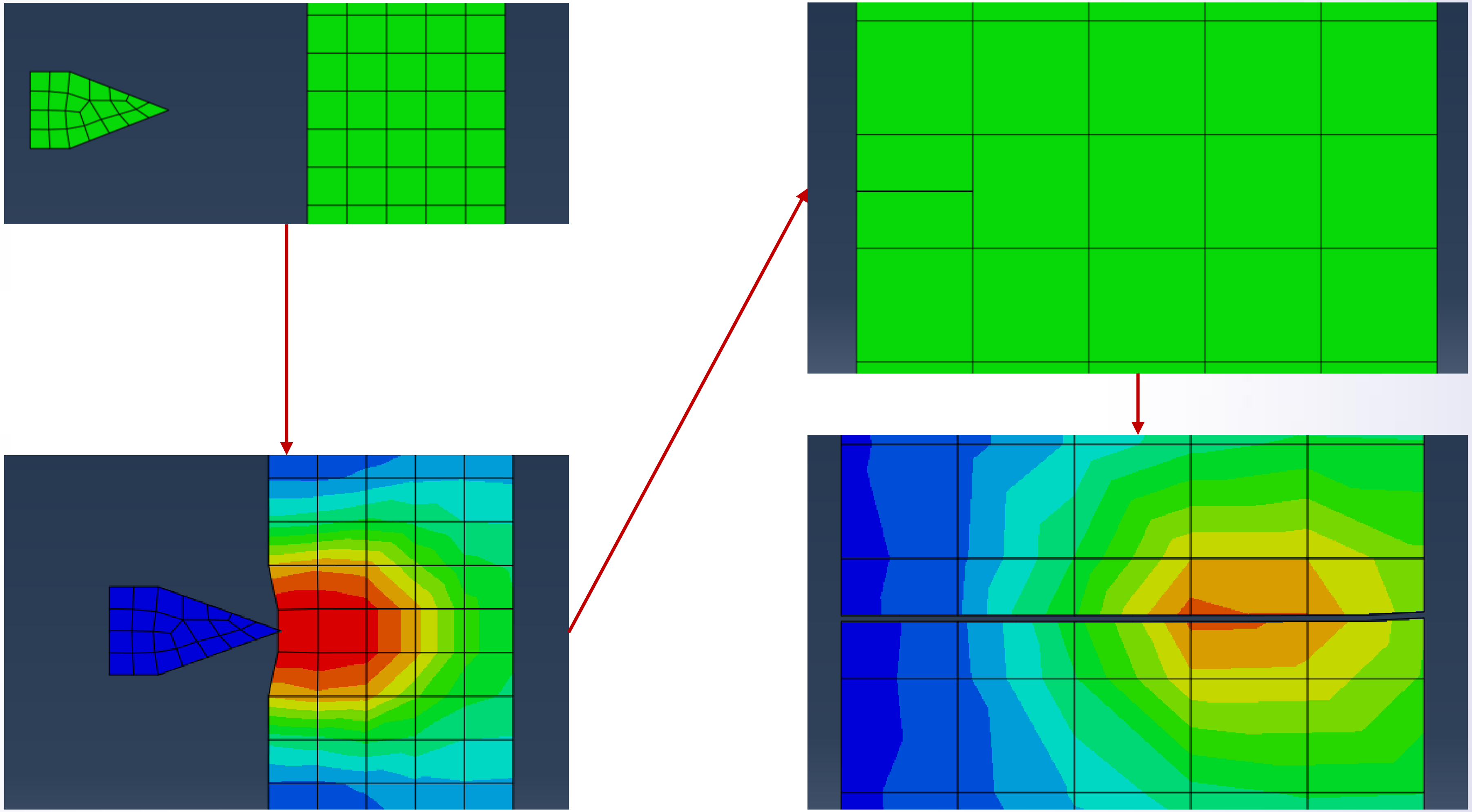

**Data from Transient Heat Transfer Model:**

Temperature at Min at Surface Point: **-59.48 °C**
Temperature at Fracturing Point: **-45.12 °C**

Energy Absorption: 15 **J/cm²**

Cooling Time: **6577 Seconds = 110 mins**

# Fracture Propagation Research



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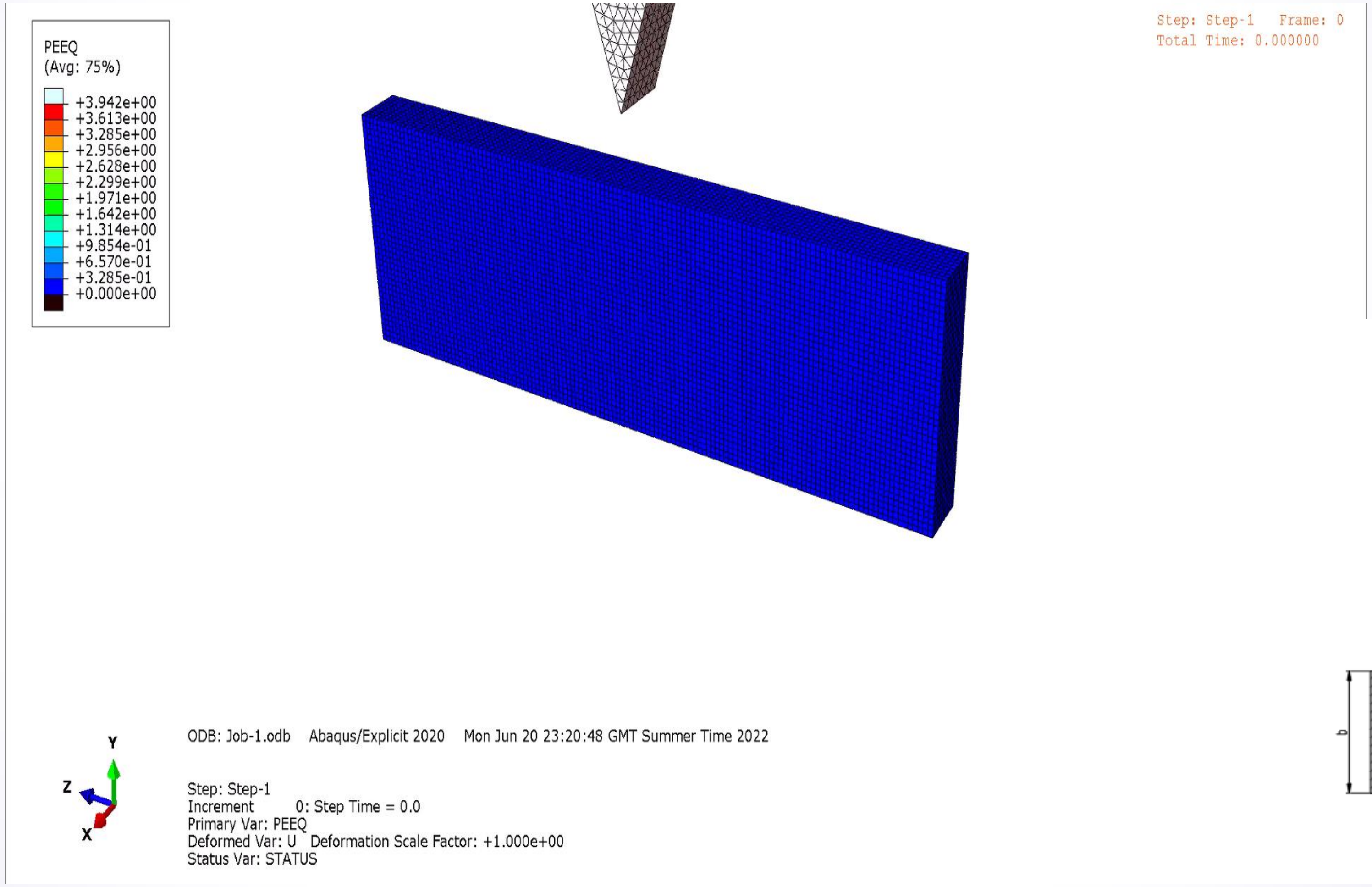
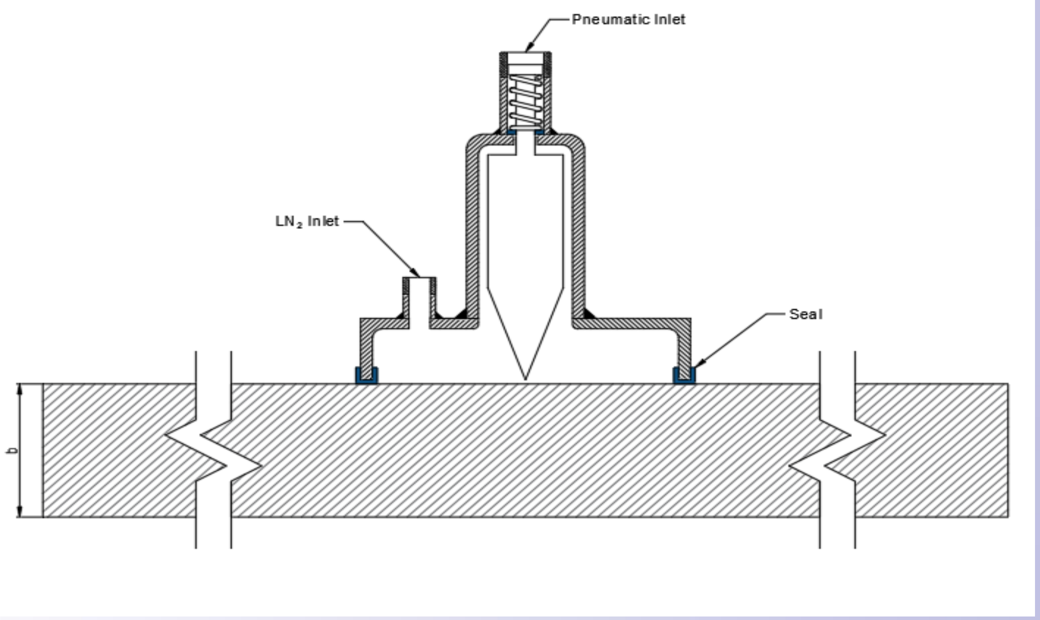
# FEA and Fracture Mechanics



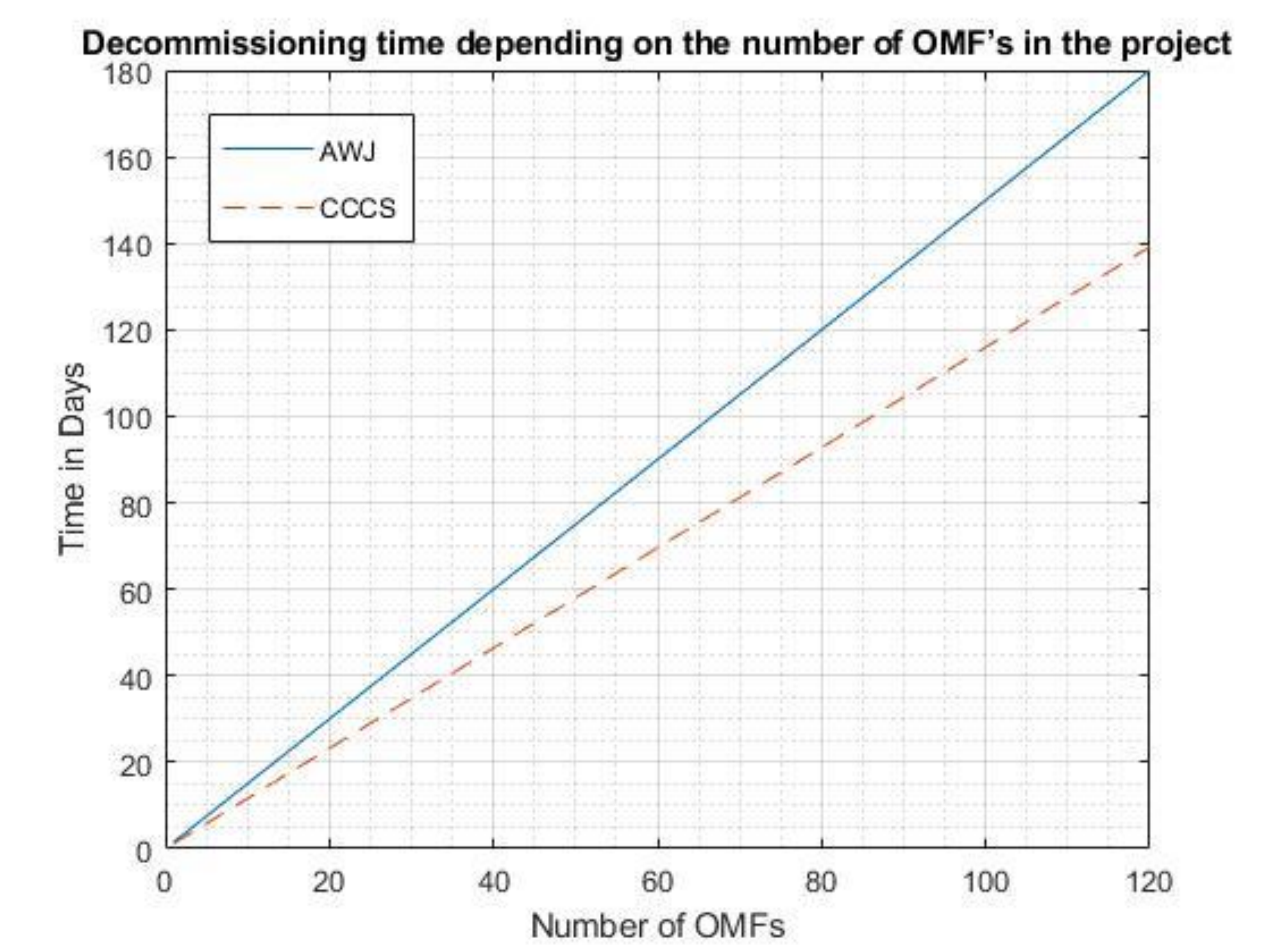
# Economic Case Study of the Cape Wind Offshore Windfarm (OMF)

**Compare cutting time of AWJ and CCCS:**

**Cape Wind OMF:**

- Internal Cutting of: **101 OMFs**
- OMFs Wall Thickness: **100 mm**

# Decommissioning Time of OMFs




**Cutting Time for 101 OMFs:**

**AWJ:**

151.5 Days

**CCCS:**

117.0 Days

**Reduction of:**

34.5 days = 22.8%

# Estimated Savings Applying the CCCS

Table 6. The vessel costs for the foundation removal operation in the Cape Wind OWF with 101 monopiles using CCCS and AWJ cutting techniques

| | | AWJ | | | | CCCS | | | |
|---|---|---|---|---|---|---|---|---|---|
| Vessel | Leasing rate (£/day) | Duration per monopile | Overall duration | Cost per monopile (£) | Overall cost (£) | Duration per monopile | Overall duration | Cost per monopile (£) | Overall cost (£) |
| JUV | 100 k | 1.50 | 151.50 | 150 k | 15.15 m | 1.16 | 117 | 116 k | 11.7 m |
| BV | 12.9 k | 1.50 | 151.50 | 19.35 k | 1.95 m | 1.16 | 117 | 15 k | 1.51 m |
| TB | 8.6 k | 1.50 | 151.50 | 12.9 k | 1.30 m | 1.16 | 117 | 10 k | 1.10 m |
| | | | | **Total:** | **18.40 m** | | | **Total:** | **14.31 m** |

The Saving of the OMF decommissioning amount to **22.8%**

**2.8%** Greater than the min target of **20%** set by the DecomTools Project

**Estimated Savings:**

**Time Saving:**

34.5 Days

**Economic Saving:**

£4.09 million

Or roughly

€4.65 million

# References


1. C. R. Brett, D. A. Gunn, B. A. Dashwood, S. J. Holyoake, and P. B. Wilkinson, “Development of a technique for inspecting the foundations of offshore wind turbines,” *Insight - Non-Destructive Testing and Condition Monitoring*, vol. 60, no. 1, pp. 19–27, 2018.
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3. M. Ejima, K. Singh, P. Maskulrath, and J. Gaskin, “Cape wind: The collapse of the United States' inaugural offshore wind farm project,” *Student Research on Environment and Sustainability Issues*, 2015. [Online]. Available: https://environment.geog.ubc.ca/cape-wind-the-collapse-of-the-united-states-inaugural-offshore-wind-farm-project/. [Accessed: 12-Jan-2023].
4. K. Bisgaard Christensen, S. Jalili and A. Maheri, “A Comparative Assessment of Cutting Techniques applied for Offshore Energy Structures ,” *2022 7th International Symposium on Environmental Friendly Energies and Applications (EFEA),* pp. 01–06, 2022.
5. K. Bisgaard Christensen, S. Jalili and A. Maheri, “Cryogenic cooling and cutting system: A novel cutting technique for offshore monopile foundations,” *Under Review,* pp. 01–24, 2023.
6. K. Sandal, A. Verbart, and M. Stolpe, “Conceptual jacket design by structural optimization,” *Wind Energy*, vol. 21, no. 12, pp. 1423–1434, 2018.

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