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Feasibility study of a nuclear powered blended wing body aircraft for the Cruiser/Feeder concept

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Keywords: *Cruiser/Feeder, blended wing body, nuclear propulsion, in-flight passenger exchange*

Abstract

This paper describes the conceptual study of a nuclear powered blended wing body aircraft for the cruiser/feeder concept. According to this radically new aviation paradigm, large transport aircraft (cruisers) carry passengers over long distances, while remaining airborne for very long periods. Smaller aircraft (feeders) take off from local airports, intercept the cruiser, dock and enable in-flight exchange of passengers and supplies. Preliminary studies indicated that cruiser concepts based on engines burning kerosene would be too heavy and feeders would need to operate also as tankers. Propelling the cruiser with a nuclear power source would yield very high efficiency parameters, even if the weight of the system would result higher due to the required reactor shielding. The blended wing body configuration was selected both for its potential advantages in terms of aerodynamic and structural efficiency, as well as for the use flexibility of its internal volume, necessary to integrate power plants and shielding, accommodate 1000 passengers and host the loading/unloading station for in-flight payload exchange. The daring nature of the proposed solution is compatible to the foreseen entry into service date, which is set for the last part of this century. The peculiar nature of the aircraft under consideration has required a somehow different conceptual design approach, than generally used for conventional passenger transport aircraft. Apart from the inherent complexity related to the design of such a novel and integrated configuration as a blended wing body, the typical design approach based on the use of simple performance equations and statistics to achieve a first estimation of the main weight contributors was of little use in this case. From one side, the fuel mass used to perform the mission is just negligible; from the other, a method was necessary to account for the weight of the radiation shielding, which is a significant contribution to the overall aircraft weight. Rather than in the numerical results of the sizing process, the value of the design work described in this paper should be found in the very design approach and the preliminary ideas for integrating the passenger docking system and the nuclear power plant.

1 Cruiser/feeder Operations and Cruiser Top Level Requirements

The cruiser/feeder operational concept is currently investigated within the FP7 research project RECREATE (REsearch on a CRuiser Enabled Air Transport Environment) as a promising pioneering idea for the air transport of the future. One of the objectives of this project is to assess, on a conceptual design level, the feasibility of the cruiser/feeder operations as a potential solution to reduce fuel burn and CO_2 emission levels [1]. The operational concept is schematically illustrated in Figure 2. The cruisers take off from dedicated airfields specifically designed to account for the big dimensions of these aircraft, as well as for the safety requirements associated to the presence of the nuclear power plants. When flying at cruise altitude, the cruiser is supposed to follow a closed loop trajectory, mainly located upon oceans or un-inhabited regions. While cruising, the cruiser is intercepted at various locations by feeders, which dock and allow the exchange of passengers, crew members, goods and waste. Thanks to the nuclear power plant, the cruiser can achieve such high levels of endurance, that in

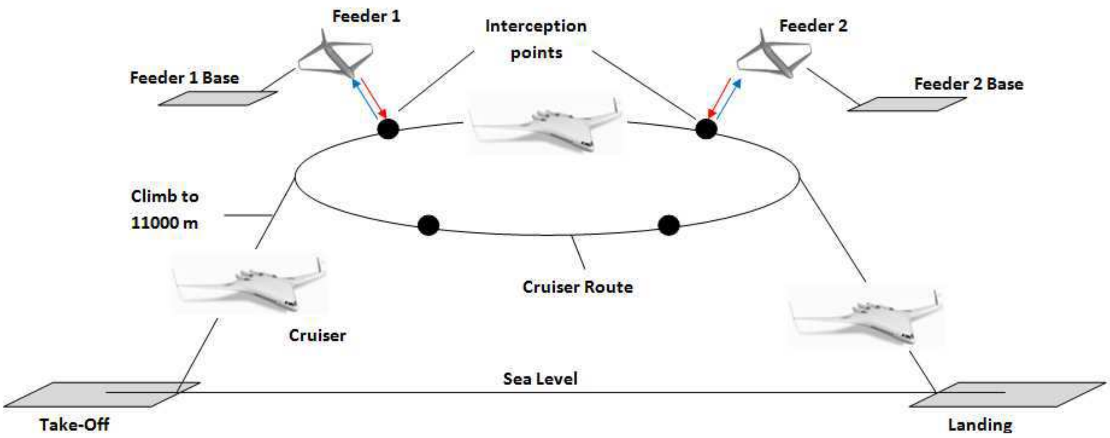

Figure 2: the cruiser/feeder operational concept

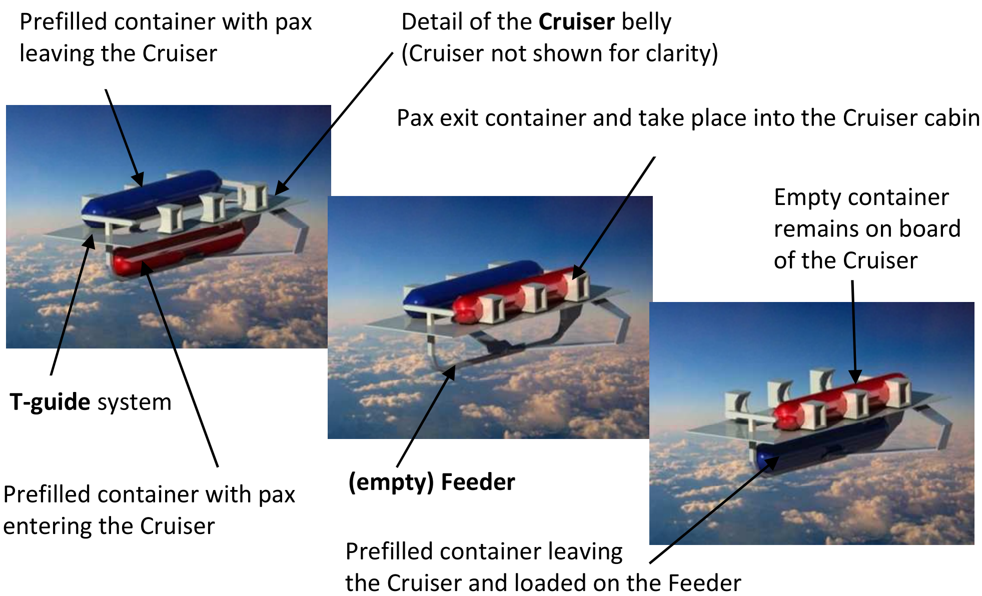

Figure 1: in flight docking and payload exchange concept

practice, the need to land is limited to the need of extraordinary maintenance, which cannot take place on board during flight, or in case of emergency.

At the moment of writing, a box wing type of configuration is considered for the role of feeder, due to its good take off and landing performance and the possibility to have direct lift control, thanks to movable surfaces that can be installed both on the front and back wings. Besides these features, the closed wing system appears a suitable structural solution to enable the detachment of the prefilled pressurized containers, which are the envisioned means to transfer payload to and from the cruiser.

The proposed docking and payload exchange approach is schematically illustrated in Figure 1. After the feeder has docked below the cruiser (a trapeze system is foreseen to facilitate the attachment of the feeder under the large cruiser belly and guarantee its stable positioning), the feeder detachable fuselage is lifted into the cruiser and, through a T-guide mechanism, shifted on one side to allow the passengers disembarking and accessing the cruiser main decks. A second detachable fuselage, prefilled with the passengers and goods that must leave the cruiser, will be loaded onto the empty feeder (using the same T-guide mechanism), in the place left vacant by the just delivered fuselage. Then the feeder will detach from the cruiser and reach the nearby landing destination. These exchange operations will be performed several times, as different feeders will intercept and dock on the cruiser, during its long range orbiting trajectory.

Parameter	***Value***	***Note***
nr of passengers	1000 PAX	100 kg each
MTOW	900000 kg	
Range	> 60,000 nm	1 week endurance
Cruise speed	M = 0.8	
Docking Speed	M= 0.7	
L/D	>20	
Cruise altitude	h_{cruise} > 11000 m	
Reactor Lifetime	Between 5000 and 10.000 hours	
Payload Transfer Concept	Single container exchange concept (100 pax each)	

Table 1: Cruiser Top Level Requirements

Table 1 collects the top level requirements established within the RECREATE project for the design of the cruiser. The high aerodynamic efficiency required for making this operational concept worthwhile, plus the demands set by the aforementioned docking and containers exchange approach, have led to the selection of a blended wing body configuration for the cruiser.

2 Preliminary Sizing Process of the Nuclear Propelled Blended Wing Body Cruiser

The peculiar nature of the aircraft under consideration has required a somehow different conceptual design approach, than generally used for conventional passenger transport aircraft. The fact that the considered configuration is a blended wing body, where the center section of the aircraft is required to perform more functions (e.g., lift generation, control, payload transfer and storage) has required an integrated and iterative approach to define the interiors layout, the aerodynamic shape and the masses distribution.

The typical aircraft conceptual design process starts with a preliminary weight estimation, where basic performance equations are used to estimate the necessary amount of fuel. From that, plus the aid of statistical data from reference aircraft, an initial estimation of the aircraft MTOW and OEW can be achieved. However, in the case of a nuclear propelled aircraft, where the amount of fuel mass used to perform the mission is negligible, a different approach was required to pursue the initial aircraft weight breakdown.

The design process implemented to achieve the preliminary sizing of the nuclear propelled blended wing body cruiser is summarized by means of the N2 chart provided in Table 4. The main phases of the design process are shown on the diagonal of the chart and all the input/output required/generated by each phase are listed on the upper and lower part of the matrix, respectively.

3 Definition of the Cruiser Planform

As a first step, the typical inside-out approach has been used to derive a suitable planform for the cruiser center body. The following assumptions have been made:

- Total deck area sufficiently large to accommodate a total of 1000 passengers in two classes.
- Cargo volume equal to 322.6 m^3. This amount was estimated on the basis of the passenger/freight ratio of existing wide body aircraft.
- Two nuclear reactors with an approximate cylindrical shape of 5 m diameter and 10 m length, including shielding (core cylinder 3m by 3 m). Two reactors were selected for pure redundancy purposes, although one would have been sufficient to deliver the required power. The initial size of the reactors was based on reference values provided by the nuclear energy experts in the consortium and will require verification, in a later stage of the project.
- Sufficient space to accommodate two fuselage-like containers (to be exchanged with the feeders), sufficiently large to transport 100 passengers and some freight. On the basis of the typical fuselage dimension of existing aircraft able to accommodate 100 passengers, it has been assumed the use of cylindrical containers with diameter of 3 m and length of 25 m.

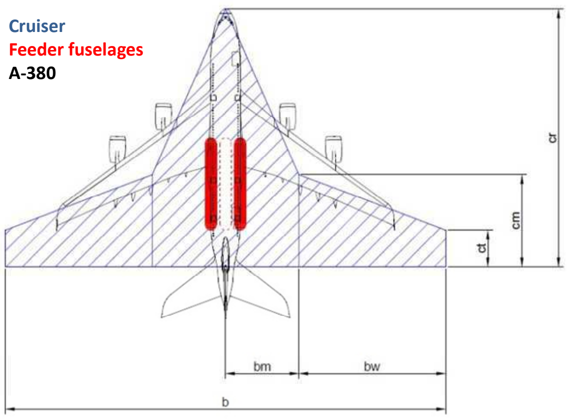

Figure 3: first iteration of the cruiser planform

The rest of the planform, i.e. the span and the shape of the actual wings of the Cruiser (in other words, the outer sections of the BWB lifting surface) was sized in view of achieving the required high aerodynamic efficiency value indicated in Table 1. To this purpose, different values of the total cruiser span have been investigated, by modifying solely the outer wing planform, until a design was found able to achieve an aerodynamic efficiency value larger than 20. A textbook method was used to estimate the parasite friction coefficient *f*, while the maximum aerodynamic efficiency was estimated using the following equation [2,3]:

$$\left(\frac{L}{D}\right)_{max} = \sqrt{\frac{\pi \cdot b^2 \cdot e}{4 \cdot f}}$$

The simple double trapezoidal planform shape (center body and outer wing) resulting from this very first iteration is shown in Figure 3. The two exchangeable fuselages (plus some space in between for the T-guide mechanism) are shown in red. The top view of an Airbus A-380 is superimposed on the picture to give a sense of the overall Cruiser dimensions. The data of this preliminary aircraft sizing are summarized in Table 2.

Description	*Symbol*	*Value*
Maximum root thickness	t_{root}	10m
Root chord length	c_r	60m
Inner part taper ratio	l_1 (c_m/c_r)	0.416
Main wing taper ratio	l_2 (c_t/c_m)	0.25
Inner part length	b_m	20m
Outer wing length	b_w	40m
Span length	b	120m
Wing Surface	S	2947m^2
Aspect ratio	A	4.89
Zero Lift Drag Coefficient	C_{D0}	0.006
Maximum aerodynamic efficiency	$(L/D)_{max}$	23.32

Table 2: Preliminary sizing and analysis of the cruiser planform

The simplified shape resulting from this preliminary sizing step was subsequently refined to account for the actual integration of payload, interiors and main systems. The external shape was refined as result of a more accurate, although simple, aerodynamic study performed with a commercial vortex lattice method tool. A limited number of airfoils was selected, scaled and twisted in order to achieve a quasi-elliptical lift distribution for minimum induced drag, while minimizing the aerodynamic pitching moment (in view of the controllability aspects) and maintaining the target value of aerodynamic efficiency. The main views of the aircraft with relevant sections are illustrated in Figure 8-Figure 10.

On the lower deck there is space for two passengers seating areas, a front and a back cargo hold, and two resting areas that can be used by passengers and the crew. In the middle, space is reserved for the pressurized containers for payload transfer (there will always be one on board of the cruiser) and the T-mechanism. The middle deck accommodates the majority of economy passengers (730 seats) and the cockpit. The top deck accommodates the business class. The two nuclear reactors are located in special bays, on the right and left side of the passenger area, well separated and isolated by protection walls. The two bays can be opened in flight to jettison one of reactors in case of emergency, without drastically affecting the longitudinal position of the aircraft center of mass.

4 Preliminary Weight Estimation

The Cruiser maximum takeoff weight WTO is the sum of the following three weight components:

- WPL (Payload Weight). It is the sum of passengers weight Wpax and cargo weight Wcargo.
- WOE (Operative Empty Weight). It includes the weight contributions of structures, engines, lubricants, and crew.
- WP (Power Plant Weight). It includes the weight of the nuclear reactors, the cooling system and the shielding. It does not include the weight of the engines, whose contribution is accounted in WOE).

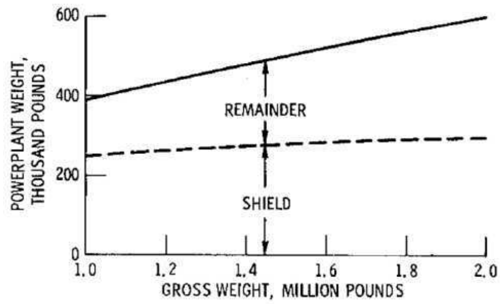

Figure 4: Nuclear power plant weight estimation

In order to estimate the Power Plant Weight WP, the key plot provided in Figure 4 is used [4,5]. Here WP is expressed as a function of WTO and is defined as the sum of two main contributions, namely the *shield* weight and the *remainder*, which includes the weight of the nuclear core and the cooling system. The following linear relation was derived based on the plot above (WTO is in 10^3 kg):

$$WP(WTO) = 0.143 \cdot WTO + 116.6$$

By expressing WOE as function of WTO, the following relation is derived:

$$WOE_I\,(WTO) = WTO - WP\,(WTO) - WPL$$

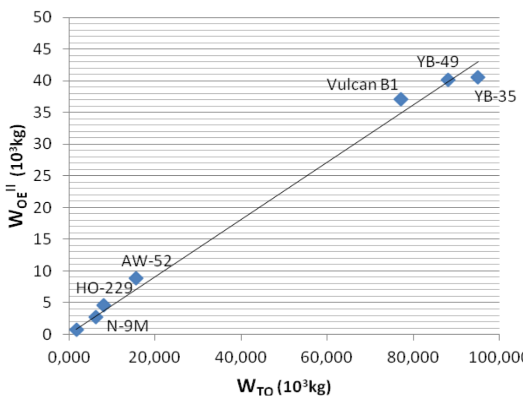

Figure 5: WOE vs WTO relation based on statistics (only blended wing body and flying wing considered)

A second equation is required to derive WOE and WTO. To this purpose, statistical analysis has been performed to derive a relation between WOE and WTO, where only flying wing type of

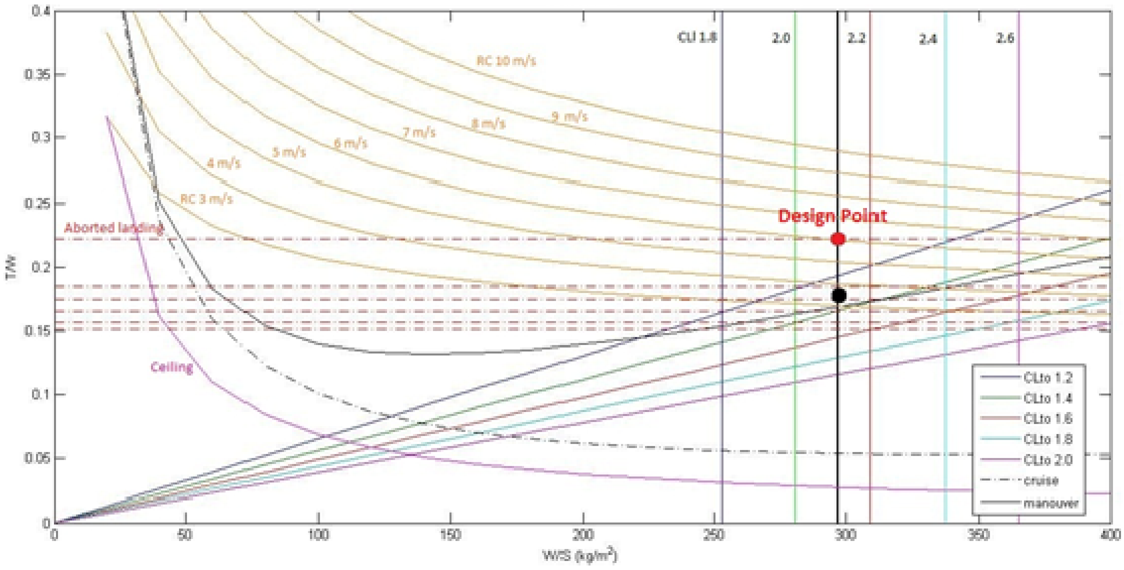

Figure 6: Wing loading vs thrust loading plot and cruiser design point

aircraft have been taken in consideration. The result is shown in Figure 5, from which the following equation was derived (WTO is in 10^3 kg).

$$WOE_{II}\,(WTO) = 0.46 \cdot W_{TO}$$

By imposing $WOE_I = WOE_{II}$ it is possible to derive a first estimation of WOE, WTO, and WP. The results are shown in Table 3 and compared to the values of the two largest wide body passenger aircraft now in operations, namely the Airbus A-380 and the Boeing B747-800 [6]. It can be noticed that WTO is lower than the value provided as top level requirements, while the estimated payload weight percentage is almost twice the value of the wide body aircraft considered in the comparison.

	Cruiser	*% W_{TO}*	*A-380*	*% W_{TO}*	*B-747*	*% W_{TO}*
W_{TO} (10^3kg)	**875**	-	560	-	343	-
W_{OE} (10^3kg)	**383.3**	**43.7**	277	49.5	212	61.8
W_{PL} (10^3kg)	**250**	**28.6**	85	15.2	60.5	17.6
W_P (10^3kg)	**241.7**	**27.6**	-	-	-	-
W/S (kg/m^2)	**297**	-	662.7	-	850	-

Table 3: Weight breakdown of the cruiser & comparison with A390 and B747

The particularly low wing loading of the cruiser is noteworthy. BWB have generally low wing loading (around 350 kg/m^2), although not as low as the cruiser. At this stage it was not possible to increase it by reducing the wing area, because this reduction could have been achieved only affecting the outer wing area (the planform area of center body being dictated by the interiors constraints discussed above). Reducing the outer wing area would have induced a negative effect on the maximum L/D and a reduction of the cooling system area, now assumed to be integrated in the wing.

5 Required Thrust Estimation

In order to estimate the required thrust and power plant power and then proceed with the selection of appropriate engines, the classical wing loading (W/S)–thrust loading diagram (T/W) plot was generated. To this purpose, a number of possible sizing conditions (take off, landing, stall, climbing, ceiling, maneuver) was selected, as detailed in Table 5. The final plot is shown in Figure 6. The design point (red dot) is set by choosing the minimum thrust required to meet all the operational requirements, at the maximum allowed wing loading computed in the previous section.

It can be noticed that for take-off and landing, the following value of maximum lift coefficient are sufficient: CL_{TO} = 1.4 and CL_L= 2.2. Both these values are relatively low, when compared to those of conventional wide body aircraft (up to CL_L = 3). This is mainly a consequence of the low wing loading of the cruiser.

The sizing requirement for T/W appears to be the one related to aborted landing with one engine inoperative (OEI). It follows that a total thrust of 1900 kN is required, which could be provided by four engines similar to the GE-115B. This is currently the most powerful jet engine and can provide a maximum thrust of 512 kN [7].

For what concerns the power, a maximum value of 344.5 MW is required during maneuvering. This value is the one to be used to size the nuclear reactors (see Table 5).

From the graph, it is possible to estimate the rate of climb RC achievable by the Cruiser, which is equal to 6 m/s and very close to that of other wide body aircraft such as the Airbus A-380 and the Boeing B-747 [6].

6 Refined Weight Estimation approach and balance of the aircraft

In case of conventional aircraft, so called Class II methods are usually applied to estimate the weight of the main structural component groups (Wing, fuselage, empennages, etc.). The sum of these components generally yields a different operative empty weight value (WOE) than obtained during the initial weight estimation phase, using Class I methods (statistics and Breguet formulas). Hence, Class I and II methods are generally iterated until a consistent set of weight estimates is obtained. Various Class II weight estimations are available in literature [2,3], but they are not generally applicable to aircraft such as the one under consideration here, given its unconventional design and the lack of statistical values to perform suitable regressions.

To this purpose a more physics based weight estimation approach, a so called Class II and half method, has been adopted to achieve a more reliable weight estimation, at least for the primary (load carrying) structural elements of the aircraft. The employed approach is based on a method specifically developed by Torenbeek for lifting surfaces [8], which makes use of the actual loads acting on the main structural components (spars, skins, ribs) to estimate their thicknesses and thus their weight.

This method has been applied to the outer wing of the BWB, first, and then to the center body of the BWB, which is also a lifting body. This latter weight contribution was then corrected by adding the weight contribution of the internal multi-bubble structural system used to accommodate the payload and carry the pressurization loads (see Figure 10). To this purpose, the sizing approach proposed in [Ref. 9] has been used. Finally, the weight contributions of engines, landing gears and other systems are added. In this case manufacturers' data and some semi-empirical rules (such as Class II weight estimation method for landing gear) have been used.

The total weight estimation for the cruiser is computed by adding the derived structural weight contributions to the payload and the power plant system weight contributions (as computed in Section 4).

$$WTO = Wwing + Wfus + WPL + WP = 924.7 \; 10^3 \text{ kg}$$

Since the obtained weight estimation does not differ significantly from the initial Class I estimation (which was 5.4% lower), no iterations were considered necessary.

A preliminary estimation of the center of gravity (c.g.) range of the aircraft was used to define a proper positioning of the landing gear. Aerodynamic simulations have been performed to estimate the position of the neutral point and assess the controllability of the aircraft, even in the most adverse (forward) position of the c.g, at approach speed and with deployed flaps. The aircraft appears to be slightly unstable when the c.g. is in its most aft position. However, the presence of one empty payload container on board is sufficient to move the c.g. in front of the neutral point and achieve stability. More details on all the weight calculations, and the stability and controllability analysis can be found in [ref. 10].

7 Considerations on the use of nuclear propulsion

The dream to achieve a nuclear powered aircraft has existed for a very long time. Extensive research took place during the cold war [4,5]. However, environmental concerns and depletion of fossil fuel resources have recently rekindled the interest in nuclear powered aircraft also for civil applications [11]. Indeed, a turbofan engine that utilizes heat energy from a nuclear reactor, does not require fossil fuel and does not emit carbon dioxide or nitrogen oxide, therefore it does not contribute to global warming. In addition, the range potential of a nuclear powered aircraft is substantially greater in comparison with a conventional aircraft. Because energy from nuclear fuel costs only a fraction of that for fossil fuel, nuclear powered cruisers also hold out significant promise to reduce the cost of air transportation.

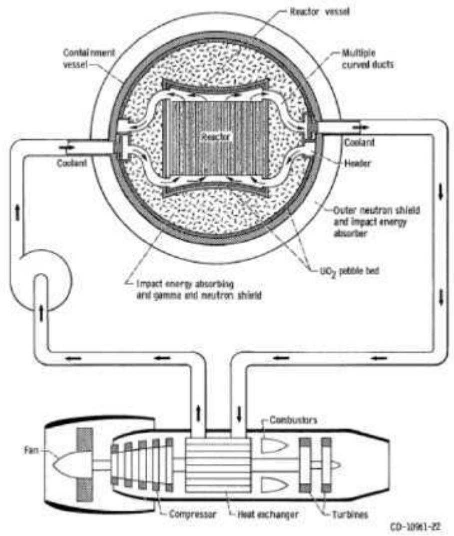

Figure 7:indirect Brayton cycle using a heat exchanger to extract the heat generated by a helium cooled reactor

The major disadvantages of nuclear propulsion are the obvious safety and security concerns. A practical nuclear cruiser design must have complete shielding to reduce the radiation doses to allowable levels in all directions, so that neither the crew and passengers onboard, nor the maintenance and servicing crew on the ground, receive radiation doses significantly greater than that normally received from natural sources. A nuclear cruiser must also have safety provisions that are designed to prevent the release of radioactive material in the worst aircraft accidents.

At the current state of work in the RECREATE project, the use of turbofan engines based on the indirect Brayton cycle and the use of compact helium cooled reactors are considered (see Figure 7), as described in [12]. Differently than a conventional gas turbine, the combustion chamber is replaced (or complemented, in case of hybrid configurations) by a heat exchanger, which transfers the heat generated by the nuclear reactor to the compressed air. Although this concept was selected because of its compactness, and the possibility to adopt a hybrid fuel system, preliminary studies reveal that, due to the poor heat transfer properties of the air, the use of helium as coolant might lead to very large heat exchanger, with severe consequences on the aircraft weight and the practical ability to place the heat exchanger between compressor and turbine. The use of another medium as reactor coolant (e.g. liquid metal or molten salt) may alleviate this problem, while retaining a compact core.

A parallel study has been performed to investigate the benefit of replacing the Brayton cycle with a Rankine cycle [13]. Indeed, this is a common solution for nuclear power stations and marine applications (large vessels and submarines). The adoption of the Rankin cycle would lead to the replacement of the turbofan engines with ducted fan engines, driven by the steam obtained from the nuclear reaction. The steam would need to be cooled down and the water sent back to the nuclear reactor in a closed loop cycle. However, this appears to be less convenient for cruiser, because of the very large condensers needed to reject the waste heat that cannot be converted into work. Although the wing surface is suited to facilitate condensation, it is not capable of rejecting all the waste heat to its surroundings (again because of air poor heat transfer properties). Extra complex and heavy air cooled condensers would be required, as well as the need to fly at lower altitude. As described in the next section, the design and integration of the nuclear propulsion system will be object of further research within the RECREATE project.

8 Conclusions and future work

The work presented in this paper represents the first step into the feasibility study of a nuclear propelled aircraft for the cruiser/feeder concept. Although the proposed concept has been supported by some preliminary calculations, significant developments are required to turn the nuclear cruiser design from an interesting exercise into a credible option for future aviation. The purpose of the RECREATE project, in this respect, is to perform only a basic exploration of this concept, to provide a preliminary assessment of the possible technical, safety and certifications related issues to be included in development roadmap. The very next steps concerning the conceptual design of the nuclear cruiser include a general review and consolidation of the results presented in the previous sections, plus the set-up of an aerodynamic analysis campaign to derive a proper combination of airfoils and planform parameters. Although a detailed aerodynamic analysis might appear premature for a concept that is still so fluid, the integrated nature of the BWB configuration requires a proper simultaneous choice of the aerodynamic shape and the rest of the parameters governing the interiors layout and the overall aircraft flight performance. Considering the absence of an actual tail, a thorough assessment of the stability and controllability performance of the aircraft, both longitudinal and lateral-directional, is necessary.

The design of the docking and loading mechanism of the detachable fuselages will require also careful attention. At the moment no sufficient information was available to propose even a simple relation to account for the weight penalty of this mechanism.

For obvious reasons, the most urgent research activities concern with the nuclear propulsion system and its integration. The number of reactors, their type (nuclear fuel and coolant), their size, the accurate sizing and weight estimation of the shielding, the layout of the energy conversion system, the choice of the Brayton or Rankine cycle to drive turbofan or turboprop engines are just some of most urgent topics to be addressed before the closure of RECREATE.

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External Inputs	• PLW • PW = PW(TOW) • OEW = OEW(TOW) • Feeder fuselage lenght • Cruise velocity • Stall velocity • Cruise altitude • T.O. distance	• Passengers Surface • Cargo Volume • Reactor Volume • Coolers Volume • L.E. sweep angle • Airfoil type • Airfoil positon	• Number of reactors • Engines Weight • Fixed L.E. and T.E. surfaces • Slats and Flaps Surfaces • Ailerons Surface • Flap Type • Material density	
	Preliminary Sizing	• Root chord lenght • Fuselage span, Wing span • Taper ratio 1, Taper ratio 2 • C_{D0c} , C_{D0} • Aspect Ratio • Wing Surface • TOW, OEW, PW • Root thickness • Tip chord, Center Line chord	• Number of engines • Reactors Weight • MZFW • MLW	
	• Aerodynamic Efficiency	**General Anrchitecture**	• t/c ratios • Coolers dimensions • Mean chord sweep angle • Volume Pressurized • Wing Surface	• 3D rendering • Mesh
	• TOW • OEW		**Detailed Weight Estimation**	
		• L.E. sweep angle • Airfoil type • Airfoil positon • Aerodynamic Efficiency		**CFD Analysis**

Table 4: N2 Chart illustrating the main design parameters computed and exchanged during the various steps of the conceptual design process

Operative Condition	*Assumptions*	*T/W*	*T (kN)*	*P (MW)*
Cruise	• $C_{D0c} = C_{D0} + 0.03$ • v = 236.3 m/s • h = 11000 m	0.053	457 @ h 1254 @ s.l.	108 300
Maneuver	• $n_{max} = 2.5$ • h = 11000 m • v = 236.3 m/s	0.17	1458	**344.5**
Take-off	• $X_{TO} = 3000$ m • Sea level			
Landing	• $v_{st} = 43.73$ m/s • Sea level			
Rate of Climb	• $C_{LTO} = 1.4$			
Ceiling	• $RC_{ceiling} = 1.5$ m/s	0.0273	234 @ h 637 @ s.l.	55.3 150
Climb Gradient	• 4 engines • $C_{LTO} = 1.4$ • $C_{LL} = 2.2$ • $v_2 = 1.2^* v_{st}$	Initial climb 0.157 Transition climb 0.165 Second part climb 0.174 Route climb 0.151 Aborted landing 0.184 Aborted landing 0.222	**1900**	100

Table 5: T/W needed in different flight conditions

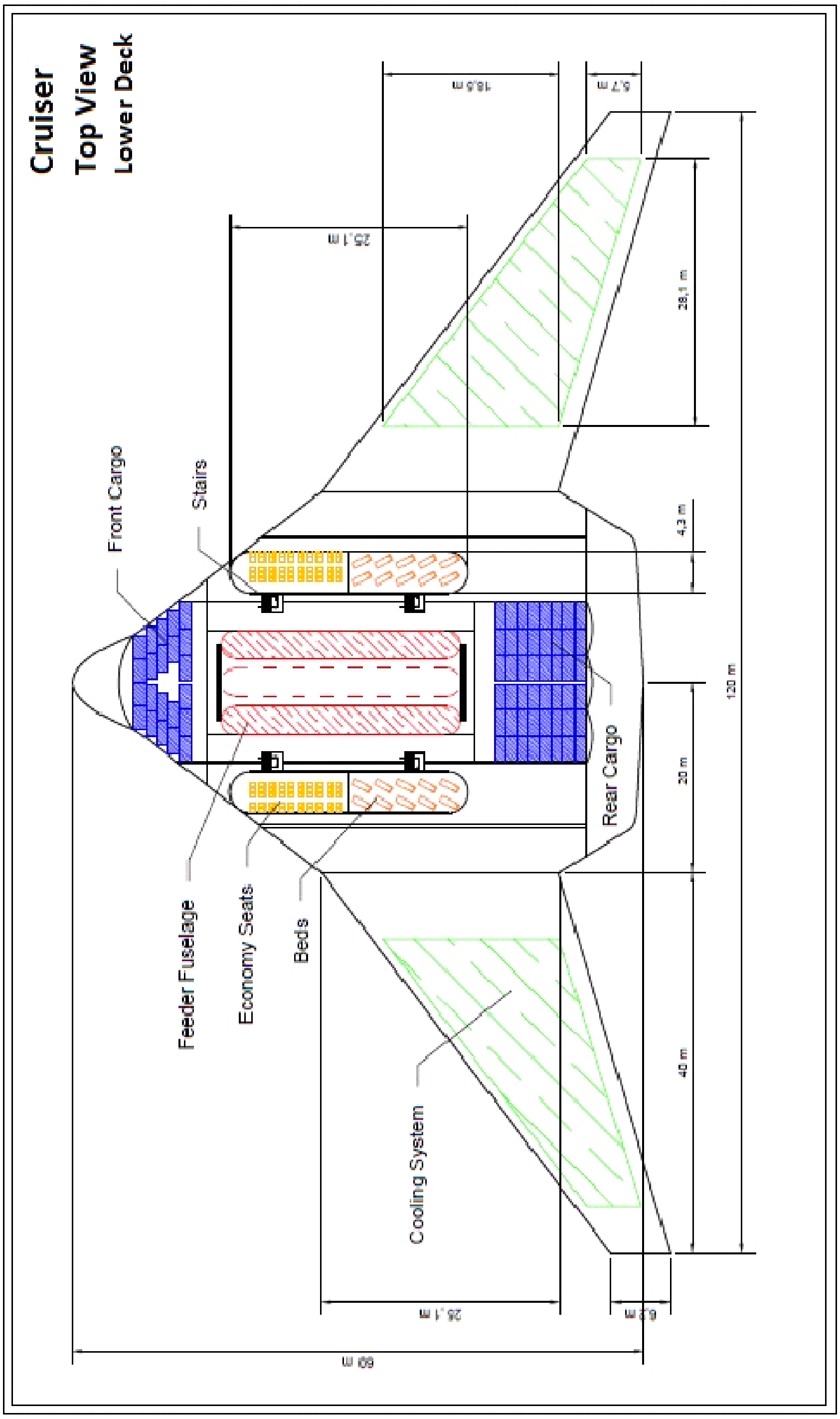

Figure 8: top view of the cruiser

Figure 9: top view of the upper and middle deck

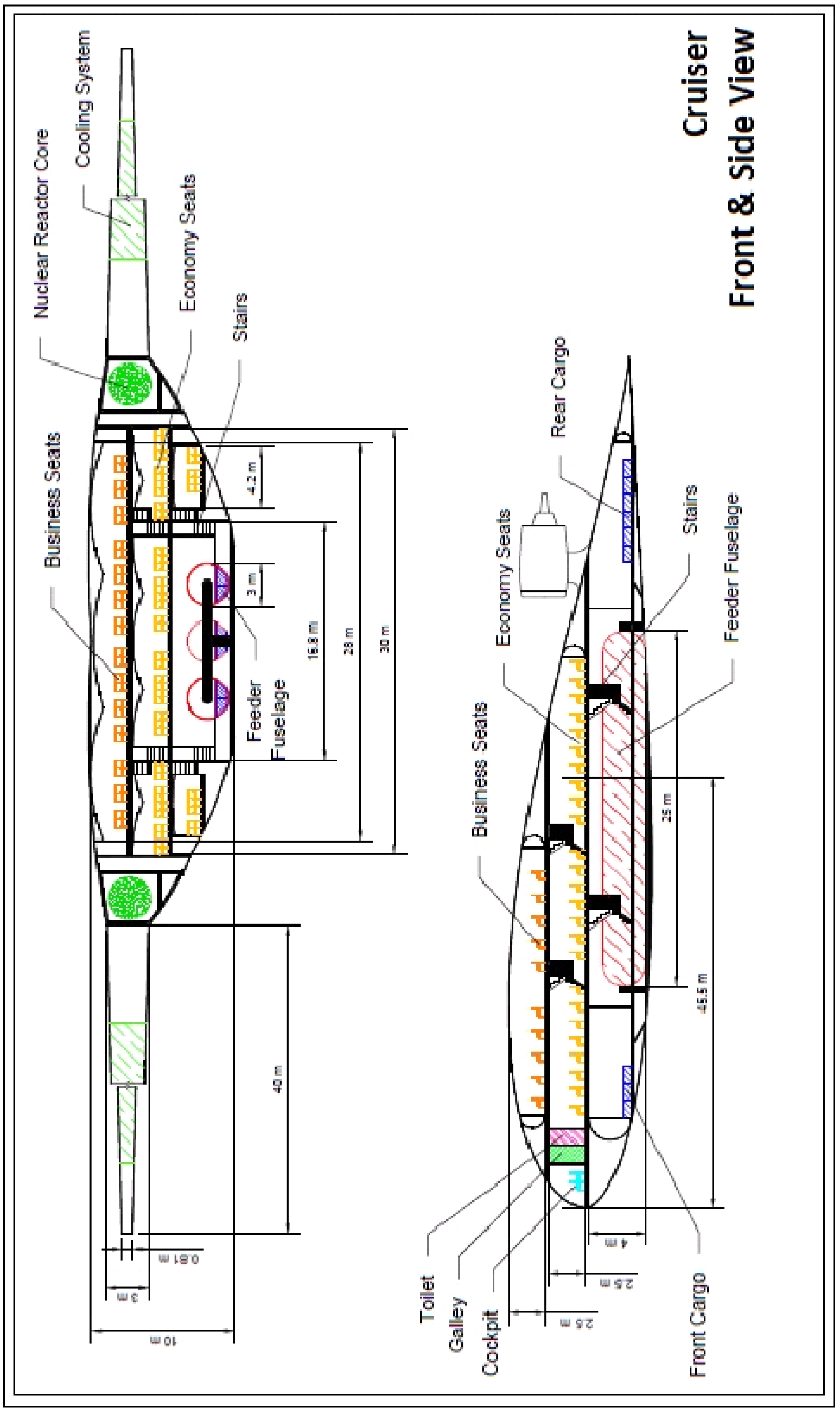

Figure 10: front and side view of the cruiser