REsearch on a CRuiser Enabled Air Transport Environment
(RECREATE)

Koen de Cock (NLR)
A brief status report, based on work performed by the RECREATE partners
NLR, DLR, FOI, TUM, TUD, QUB, ZHAW, RKN, NRG

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Price evolution 1990-2011
Kerosene-Type Jet Fuel

Projection of the world population for the years 2000-2300

Figure 6. Estimated world population: 1950-2000, and projections: 2000-2300

Source: Department of Economic and Social Affairs, Population Division, United Nations, report ST/ESA/SER.A/236
Cruiser - Feeder concept of operation

- Refers to an airborne metro system around the globe.
  - Large cruisers transport passengers over long distances, while remaining airborne for very long periods.
  - Locally, passengers, supplies and waste are transported between the local airport and the cruiser by feeder aircraft.

- The authors of the EU out-of-the-box studies suggest that the cruiser - feeder concept of operation has a huge benefit with respect to fuel consumption.

- Within the fifth call of the FP7 the EU called for research on promising pioneering ideas for energy efficient air transport of the far future
  - including the Cruiser – Feeder concept of operation.
Cruiser - Feeder concept of operation: artist impression
Could the Cruiser-Feeder concept ever bring any fuel saving?

Consider special case of cruiser-feeder operations: air-to-air refueling

Both feeder (tanker) and the cruiser are (military) derivatives of passenger aircraft.
Soundness of the Cruiser - Feeder concept of operation

- Air-to-air refuelling is the most obvious example of the cruiser - feeder concept of operation.
- Based on information available for actual aircraft
  - Statistical data of existing optimized aircraft.
- A comprehensive estimate shows air-to-air refuelling fuel burn reduction potential is
  - 31% for a typical 6000 nautical miles flight with a payload of 250 passengers,
  - smaller but still substantial savings on shorter routes,
  - significantly greater savings on larger routes.
- Airworthiness is key aspect affecting fuel burn reduction potential
REsearch on a CRuiser Enabled Air Transport Environment

Funded in the 7th Framework Programme of the EC

Project duration: August 2011 to January 2015

RECREATE Partners:
- NLR, Amsterdam, The Netherlands
- DLR Braunschweig, Germany
- FOI, Sweden
- TU Munich, Germany
- TU Delft, The Netherlands
- Queen’s University Belfast, UK
- ZHAW, Zurich, Switzerland
- Nangia Research Associates, UK
- NRG, Petten, The Netherlands
RECREATE objectives

• Substantiate suggested cruiser – feeder benefits.
• Explore pioneering case in which not only fuel but also passengers are transferred from the feeder to the cruiser.
• Top level objective:
  demonstrate on a (conceptual - preliminary) design level that cruiser - feeder operations can be shown to ever comply with the airworthiness requirements for civil aircraft.
• S&T objectives
  – Show that viable and acceptable C-F concepts exist.
  – Identify necessary procedures / required facilities AW.
  – Confirm that reported benefits are consistent with refined analysis.
WP 1 CASE - CONCEPTS FOR CIVIL CRUISER - FEEDER OPERATIONS
development and analysis of general operational concepts, assumptions, procedures, analysis of logistics, etc. WP leader FOI

WP 2 CASE - AIRWORTHINESS OF CIVIL CRUISER - FEEDER OPERATIONS
procedures and steps needed as means of compliance, regulations, analysis of failure modes, development and application of causal models for safety analysis, FAR, etc. delta on loads, flutter, loads, gust, facilities to be used in means of compliance
wake vortex separation case study as example of airworthiness regulations WP leader NLR

WP 3 CASE - BENEFITS OF CIVIL CRUISER - FEEDER OPERATIONS
analysis of impact on Greening Air Transport, analysis fuel burn / CO₂ reduction, etc. WP leader RKN
Concepts for civil Cruiser – Feeder operations

Cruiser Feeder Concepts

- No transfer of supplies
  - Direct Transfer
- Transfer of supplies
  - Container
Concepts for civil Cruiser – Feeder operations

Cruiser Feeder Concepts

- No transfer of supplies
- Transfer of supplies
RECREATE C – F Concept 1
An orbiting cruiser
RECREATE C – F concept 1
Nuclear cruiser conceptual design

Cruiser
Front & Side View
• concepts based on engines *burning kerosene with transfer of payload cannot be seen as viable*.  
  – The overall weight of the system and the total amount of fuel burnt is too high.

• However, if the Cruiser can be propelled by a *nuclear power source the efficiency parameters are very high* compared to the reference case.  
  – Even if the weight of the system is higher.

• Airworthiness is difficult (see further).

• Concept is retained for study, because it cannot be excluded that new nuclear physics will be discovered and confirmed in the future.
# Cruiser

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity, nr of passengers</td>
<td>1000 PAX</td>
<td>Assuming 100 kg per PAX. 1 week endurance; over water c only!</td>
</tr>
<tr>
<td>Range</td>
<td>&gt; 60,000 nm</td>
<td></td>
</tr>
<tr>
<td>Maximum Take Off Weight</td>
<td>2,000,000 lb</td>
<td></td>
</tr>
<tr>
<td>Cruise speed</td>
<td>M = 0.72</td>
<td></td>
</tr>
<tr>
<td>Docking Speed</td>
<td>M= 0.72</td>
<td></td>
</tr>
<tr>
<td>L/D</td>
<td>&gt;20</td>
<td></td>
</tr>
<tr>
<td>Cruise altitude</td>
<td>h_{cruise} = 20,000 ft - 25,000 ft</td>
<td></td>
</tr>
<tr>
<td>Docking Altitude</td>
<td>h_{cruise}</td>
<td></td>
</tr>
<tr>
<td>Reactor Lifetime</td>
<td>10,000 hours</td>
<td></td>
</tr>
<tr>
<td>Reactor type thermal or fast</td>
<td>thermal</td>
<td></td>
</tr>
<tr>
<td>Nuclear Propulsion System</td>
<td>ducted fan/ Rankine cycle</td>
<td></td>
</tr>
<tr>
<td>Fuel</td>
<td>hybrid chemical/nuclear fuel</td>
<td></td>
</tr>
<tr>
<td>direct or indirect cycle</td>
<td>indirect</td>
<td></td>
</tr>
<tr>
<td>Transfer Concept</td>
<td>Single container station concept</td>
<td></td>
</tr>
</tbody>
</table>

# Feeder

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity, nr of passengers</td>
<td>~100</td>
</tr>
<tr>
<td>Cruise speed</td>
<td>M = 0.8</td>
</tr>
<tr>
<td>L/D</td>
<td>&gt;17</td>
</tr>
<tr>
<td>Cruise altitude</td>
<td>h_{cruise} &gt; 35,000 ft</td>
</tr>
<tr>
<td>Transfer Concept</td>
<td>Detachable (preloaded) container</td>
</tr>
<tr>
<td>Feeders Flight Profile (Average)</td>
<td>About three to five hours flying time 500 – 1000 nm + 30 minute loiter time Time to maneuver, dock, load/unload 15 minutes (5 minutes docked), Feeder approaches and docks to cruiser from below</td>
</tr>
</tbody>
</table>
RECREATE C – F Concept 2
Air to Air Refuelling
### RECREATE C - F concept 2

**Air-to-air refuelling**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity, nr of passengers</td>
<td>250</td>
<td>Assuming 100 kg each.</td>
</tr>
<tr>
<td>Range</td>
<td>2500-3000 nm</td>
<td></td>
</tr>
<tr>
<td>Maximum Take Off Weight</td>
<td>240 000 lb</td>
<td></td>
</tr>
<tr>
<td>Specific Fuel Consumption</td>
<td>0,525</td>
<td></td>
</tr>
<tr>
<td>Position of receptacle</td>
<td>Front upper fuselage surface</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Offload Capability fuel</td>
<td>35 000 lb</td>
<td>Three times</td>
</tr>
<tr>
<td>Range</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feeders Flight Profile (Average)</td>
<td></td>
<td>About Four hours flying time</td>
</tr>
<tr>
<td></td>
<td></td>
<td>500 nm - #1- Loiter 30 min - #2 – Loiter 30 min #3 – 500 nm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>AAR procedure 20 minutes with Wet Contact 5 minutes</td>
</tr>
<tr>
<td>Position of boom</td>
<td></td>
<td>Aft rear fuselage surface, pointing backwards and down</td>
</tr>
</tbody>
</table>
Airworthiness of Cruiser - Feeder
Means of compliance with regulations

- An approach similar to autoland certification could be feasible
  - Simulate from approach initiation point until abort.
    - How many simulation runs?
  - Validate simulation models with flight test results.
    - How many flights?
  - Perform for all cruiser feeder aircraft combinations.
Airworthiness of Cruiser - Feeder
List of aspects to be considered

- Aircraft dynamics (including flight control system)
- Autopilot control laws
- Position determination system accuracy
- Probability of wind, wind shear, turbulence
- Aerodynamic interaction between cruiser and tanker
- System tolerances
- Aircraft weight and c.g. location (including changes due to fuel consumption)
- Approach procedure
- Aircraft geometry
- Boom dynamics (including boom control system)
- Boom control laws
- Boom position determination system accuracy
- Detection time of wind, wind shear, turbulence > limits
- Abort procedure
- Boom retraction procedure
- System failures should be considered according to CS25.1309: engine, flight control system, autopilot, position determination system, boom flight control system, boom autopilot, boom position sensors
- Detection time of system failures
- Flight crew errors
Airworthiness concerns C-F concept 1
Loss of coolant system nuclear cruiser

- Detection of imminent crash => shut down reactor
  - However this is not achievable with a sufficiently small probability.
- Thus a working reactor when crashing must be considered.
  - In case of crash over water, cooling can be done by water itself. How, if reactor containment vessel is closed?
- Over land the reactor is not allowed to operate and must be shut down.
  - But if the cruiser must perform an emergency landing, with the reactor shut down but still cooling down, there is a relative high risk of an accident and consequent loss of cooling system.
    - Could a meltdown occur in this case?
    - And does this mean that the core will melt through the containment vessel?
- Coolant system should be able to withstand incidents like engine rotor burst, explosive decompression.
  - With probability > $1 - 10^{-12}$?
  - Safety barrier of jettisoning reactor in sea acceptable even if this occurs once every 100 years?
Suppose the reactor containment vessel can withstand collisions (apart from head-on collisions), crashes and engine rotor burst.

- In this case the probability of a head-on collision must be smaller than the allowable probability of excess radiation / radioactive elements entering the atmosphere. \( \text{Probability} < 10^{-12} \)?
- Note: a head on collision can also be caused by an act of terrorism.

If the containment vessel ruptures it is stated that in the water only the least radioactive materials will escape.

- \textit{The other fission products are dissolved (?) or trapped (?) in water. No risk?}

This does not provide a barrier because the head-on collision occurs in the air.

- Also the vessel can rupture over land with the reactor shut down.
Is additional shielding required, apart from the reactor containment vessel?

- In this case the shielding must be able to cope with non-fatal accidents like explosive decompression, engine rotor burst, collisions on the ground. Otherwise passengers and wreckage clearance personnel are exposed to radiation.

- With probability > 1 - 10^{-12}?
Traffic simulations / cost analysis
Cruiser Network by Scenario

Transatlantic Scenario
3000nm Cruiser

Europe-Asia Scenario
3000nm Cruiser

Europe-Asia Scenario
2500nm Cruiser
Design optimization runs have been conducted for 3 designs:
- wing size was reduced according to reduced weight,
- fuselage size was maintained,
- takeoff field relaxed to $BFL = 2000 \text{ m}$, $m_{\text{freight max}}$ reduced to 5 to.

<table>
<thead>
<tr>
<th>No refueling</th>
<th>One refueling</th>
<th>Two refuelings</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L/D = 18.9$</td>
<td>$L/D = 17.9$</td>
<td>$L/D = 17.5$</td>
</tr>
<tr>
<td>$\Delta m_f = 0%$</td>
<td>$\Delta m_f = 20.6%$</td>
<td>$\Delta m_f = 24.9%$</td>
</tr>
</tbody>
</table>
Design optimization runs have been conducted for 3 designs:
- wing size was reduced according to reduced weight,
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**no refueling**
- $L/D = 18.9$
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**one refueling**
- $L/D = 17.9$
- $\Delta m_f = 20.6\%$

**two refuelings**
- $L/D = 17.5$
- $\Delta m_f = 24.9\%$
2 families of tankers designed for 10 specific missions (radius & number of refuelling ops)

Nomenclature as following:

**T-250-3:**
- Conventional tanker
- Design refueling radius: 250nm
- Refueling num. of cruisers: 3

**TF-500-5:**
- Flying-wing tanker
- Design refueling radius: 500nm
- Refueling num. of cruisers: 5
RECREATE C – F concept 2
Family of mission optimized tankers

Size comparison
Conclusions

• Two RECREATE initial cruiser concepts defined, second iteration now ongoing.

• C-F impact on aircraft and on air transport environment as a whole is studied.

• RECREATE is close to the formulation of a roadmap towards airworthiness.
  – For RECREATE concept 1 (nuclear cruiser) airworthiness is not within reach; awaiting discovery and confirmation of new disruptive nuclear physics
  – For RECREATE concept 2 (refuelling) similarity with airworthiness of autoland solutions is suggested. AW of RECREATE concept 2 is now judged as being feasible.

• Conceptual and preliminary design study of optimized aircraft required ongoing.

• First assessments (independent of statistical estimates) of benefits in terms of fuel savings is obtained for RECREATE concept 2.
  – Fuel burn saving does not always lead to cost saving

• In depth study and design is ongoing on advanced automatic flight control concepts necessary to reduce the workload of the pilots and concepts for docking

• First flight simulation experiment to investigate pilot Human Factors of cruiser - feeder operations concept has been successfully conducted, yielding valuable feedback of pilots

• RECREATE C-F concept 2 is a promising pioneering idea, for energy efficient air transport beyond 2050