2002-01-2447

ISS Crew Refrigerator Freezer Rack - Comparing EcosimPro and ESATAN Modeling

R. Müller, M. P. Hess, B. Hummelsberger, J. Winter
Astrium GmbH, Friedrichshafen, Germany

L. Eicher
FH Konstanz, Konstanz, Germany

O. Pin
ESA/ESTEC, Nordwijk, The Netherlands

R. Pérez-Vara
Empresarios Agrupados, Madrid, Spain

ABSTRACT

The Crew Refrigerator/Freezer Racks (RFR) are being developed and built at Astrium Friedrichshafen under ESA contract. The RFR will provide conditioned storage volume for astronaut food during transport in the MPLM and on board the ISS.

To support the design of the RFR a thermal model has been established at Astrium in the early project phase using the ESATAN software which is the ESA standard thermal analysis tool. This model has been extended to allow full operational simulation of the RFR during a typical mission scenario.

For demonstrating the capabilities of EcosimPro, a state of the art tool to address Environmental Control and Life Support analysis, the same model is built up with EcosimPro. The results are validated by comparing them to those from the ESATAN simulation.

Three simulation cases are investigated:

- steady state operation mode,
- 8 hours passive period with increase of ambient temperature from 30 °C to 49 °C and recovery,
- door opening every 3 hours for up to 30 seconds at ambient temperature of 30 °C.

INTRODUCTION

A detailed ESATAN thermal model of the Crew Refrigerator Freezer Rack has been established at Astrium Friedrichshafen in order to follow the development and support the design phase. . This model is continuously updated to accompany the design progress.

An EcosimPro thermal model was developed by ESTEC in an early phase of the project, this model being used for shadow engineering purposes. The objective of the present activity was to upgrade this EcosimPro model in order to achieve a level of detail similar to the ESATAN model, to be able to compare the results obtained with the two tools and to compare their respective capabilities.

The RFR design status at PDR has been taken for this comparison.

RFR GENERAL DESIGN

Figure 1 shows the Crew Refrigerator/Freezer Rack. It can be structured in the following subsystems:

1. Rack Subsystem

The RFR components is accommodated in a RFR specific Boeing 4-post rack. This is a so-called 'Dash-7' type composite rack.

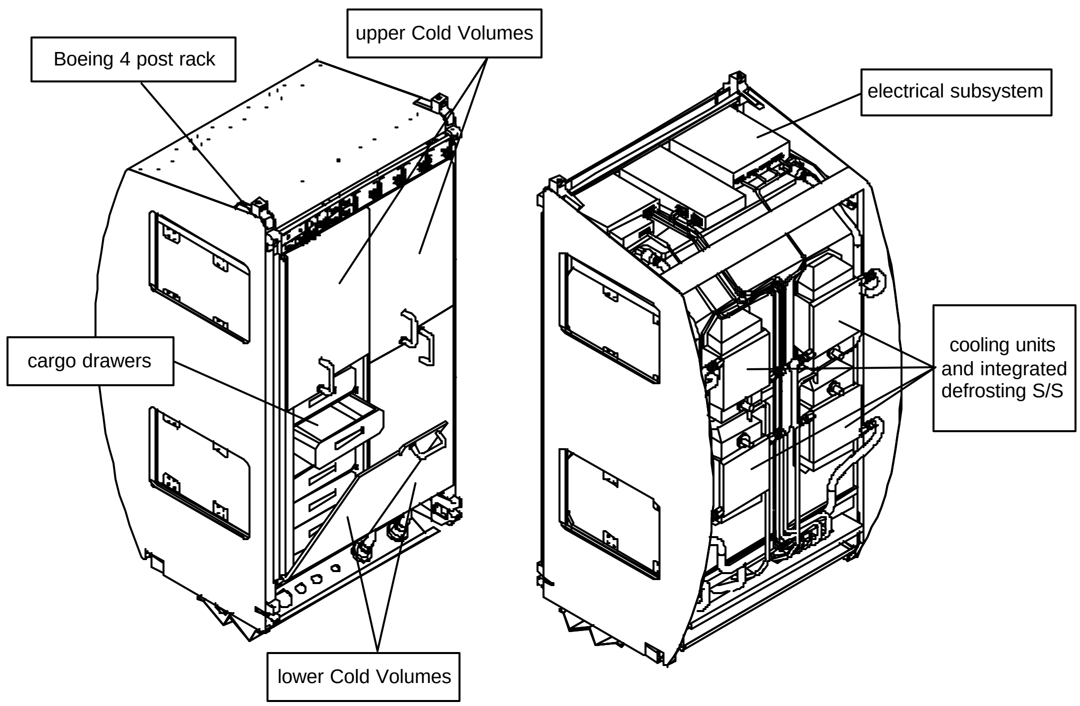


Figure 1: Crew Refrigerator/Freezer Rack

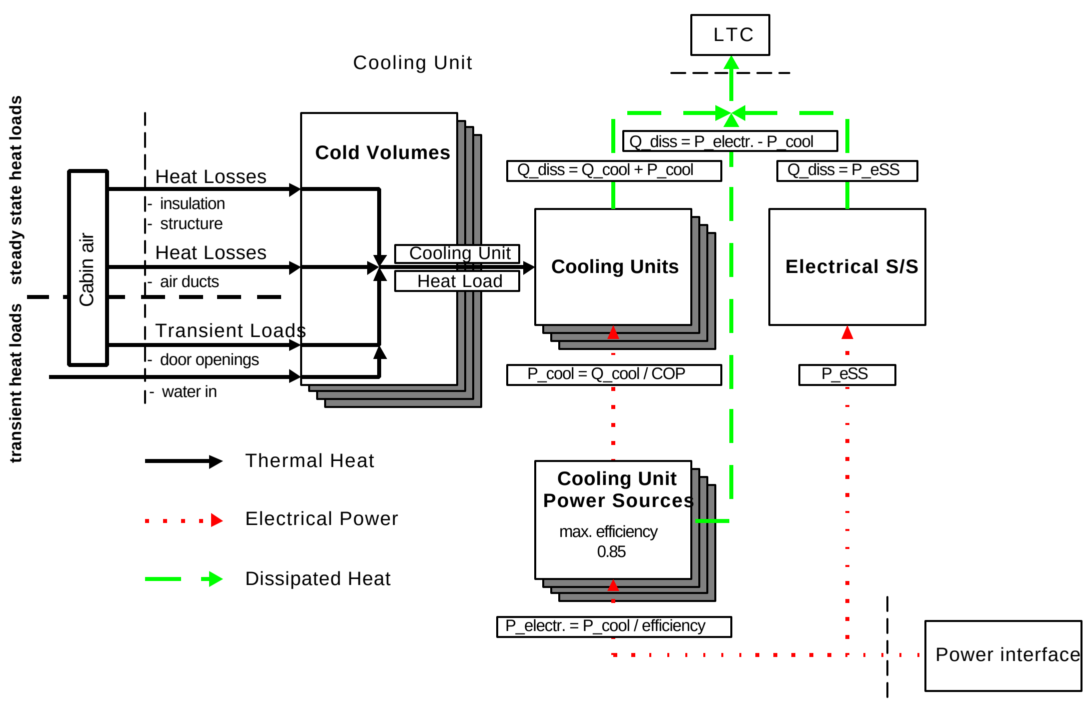


Figure 2: RFR Thermal System Budget Map

2. Cold Volume Subsystem
Each RFR has four individual Cold Volumes, which are built as monolithic structure from G/CFRP. The Cold Volumes provides thermal and mechanical protection against ambient. The Cold Volumes will be the envelope for the cargo drawers, in which the food packages can be accommodated. Each of the two upper Cold Volumes includes 5 cargo drawers and each of the two lower Cold Volumes includes 6 cargo drawers, leading to a total number of 22 cargo drawers.

3. Cooling Subsystem
The cooling system is based on Thermo Electric Cooling Modules (TEC). The cooling units will collect thermal energy from the RFR Cold Volumes by means of a forced convection airflow that passes by an air heat exchanger and distributes the heat at a higher temperature level to the station's Low Temperature Cooling Loop. Each of the four Cold Volumes has it's own cooling unit. The temperature of each Cold Volume can therefore be controlled individually to refrigerator mode or freezer mode. The Low Temperature Cooling Loop flow is divided in two single flows routed through the left and right side Cold Volumes from lower to upper part in parallel and then joint together prior to routing it through the cold plate cooling the electrical subsystem.

4. Electrical Subsystem
The electrical subsystem is located on top of the upper Cold Volumes and will handle all external and internal interfaces (e.g. commands, data, power). Also RFR internal functions (e.g. temperature control, fan control, defrosting) are managed by the electrical subsystem.

5. Defrosting Subsystem
The humidity entering into the Cold Volumes through leakages and especially during door opening will accumulate on the air heat exchanger of the cooling unit. This frost will be removed during 30 minutes per day, when the cooling air flow is automatically switched off and the TECs are switched from cooling to heating mode. The frost from the heat exchanger fins melts and the resulting water is removed by a dedicated system using capillary forces. Then the water is pumped to a collector/evaporator unit from where it will be returned to the cabin air by controlled evaporation.

RFR THERMAL MODEL

GENERAL THERMAL MODEL

The RFR subsystems are shown in the system budget map (figure 2), together with the main thermal active parts. The diagram shows the sources of heat intake into the system and the heat dissipation path, including the electrical power sources.

Figure 3 shows the principle thermal model as it is realized in the EcosimPro as well as in the ESATAN Model.

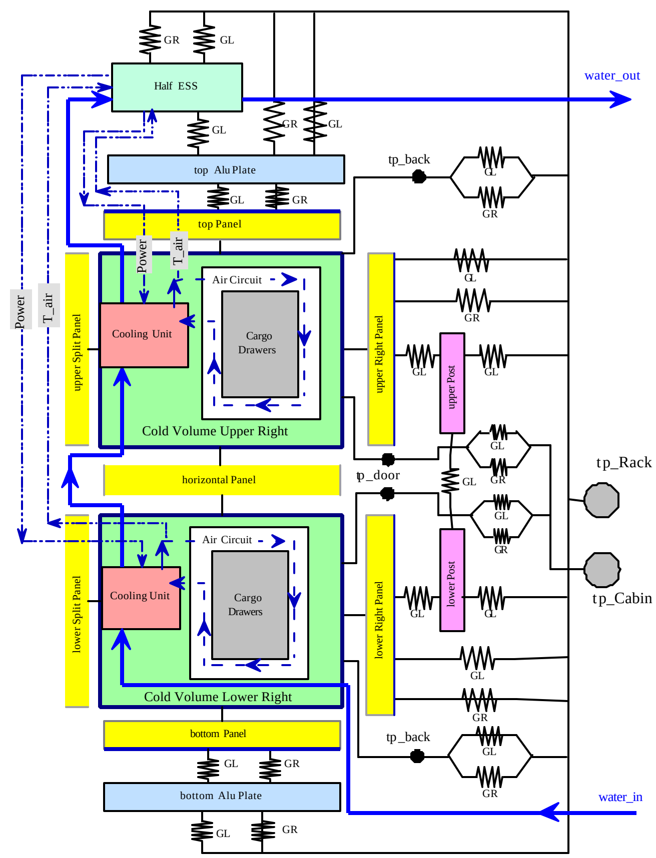


Figure 3: RFR Thermal Model

The active thermal parts in this system are:

?? The four cooling units, based on thermo electric coolers, which cool the internal air to the required set temperatures. In order to calculate the performance of the thermo electric coolers depending on the load case and the boundary conditions a physical model of the thermo electric coolers has been established. Input for this model is the necessary heat to be removed from the air and the given set-temperature as air outlet temperature of the heat exchanger. Output is the necessary electrical power. Influencing boundary conditions are the water inlet temperature, and derived from that the mean temperature of the thermocouples. The model has been verified with test data and corresponds well with real performance data.

?? Each cooling unit also includes a fan which produces the Cold Volume internal airflow with electrical power input and corresponding heat dissipation to the internal air of 4 W.

?? The electrical subsystem comprises the power supplies (current source) and the controller. The efficiency of the power supply to the fan and the thermo electrical coolers is 0.85 and the power consumption of the Electrical Subsystem itself is assumed with 61 W.

All the other components are passive components:

?? The rack structure consists of the four rack posts holding the Cold Volumes, the rack outer covers, a lower structural plate and an upper structural plate. The rack outer covers are used as a boundary node for which the temperature is given as boundary condition.

?? The walls of the Cold Volumes consist of vacuum insulation panels, having a thermal conductivity of less than 0.006 W/(m K), between an outer Aluminum face sheet and an inner GFC face sheet, additionally connected by GFC struts for structural enforcement. The internal modeling represents the cargo and the cargo drawers which are thermally coupled to the Cold Volume side walls via the drawer rails and radiative and conductive coupling over an air gap. The air flow, that cools the cargo drawers and collects the heat input from ambient, circles through the Cold Volume from the cooling unit through top gap, front gap, bottom gap and backside gap between the drawers and the Cold Volume Wall Panels. When the air flow is stopped during door opening or when the RFR is not powered, heat exchange is via conduction over the air gap. Externally the Cold Volume is connected to the rack walls via screw interfaces to the side posts and to the top/bottom structural Aluminum plate. Further the heat exchange is modeled using conduction over the air gap between Cold Volume walls and Rack walls as well as via radiation.

?? The cabin is defined as a boundary node. The heat exchange with the cabin is done via the door surface assuming convective heat exchange with 1W/(m²K) as well as radiation assuming a radiative emission coefficient of 0.4 for the door surface.

DIFFERENCES BETWEEN THE ECOSIMPRO AND THE ESATAN THERMAL MODEL OF THE RFR

RFR Model Structure

The RFR is build up symmetrically to the centerline with a left and a right half of upper and lower Cold Volume each. The Electrical Subsystem is one common unit supplying both RFR halves.

In the ESATAN model two identical submodels are joint together by one main model. The main model includes the Electrical Subsystem and its interfaces to the submodels and the common structural plates at the top and bottom of the rack.

In the EcosimPro model, only one half is modeled, with the Electrical Subsystem assumed to be also separated to two identical halves. The total heat and power budgets are then to be calculated by doubling the half model data. This simplification seemed to be feasible due to the symmetrical design. However, a full RFR model could have been easily established in EcosimPro but the impact on the calculation results should be marginal.

The EcosimPro model has been better structured by having separate submodels which are in principal selfstanding and are connected via interface ports to the full system model. Also similar components (like a Cold Volume including a cooling unit and an air circuit), are modeled once in submodels and then are used several times. They are called in the higher level model with the specific parameters and geometry data submitted to generate individual components. This good structurization results in a good overview of the model. Also the submodels can be easily used selfstanding and verified separately before they are put together to the whole system.

Modeling of the Cooling Unit

The physical model that has been established to simulate the performance of the thermo electrical coolers leads to a non linear equation system resulting in three equations with three unknowns. A FORTRAN solving routine using the Newton-Raphson-Method needed to be programmed for the ESATAN model whereas EcosimPro solves the equation system using the EcosimPro internal solvers. This made the programming work much easier and also the convergence of the model could be realized better due the EcosimPro specific tracing to failure resolution.

Modeling of the RFR Structure and Thermal Connections of Nodes

The thermal connectors between the Cold Volumes and the Rack are built up much more detailed in the ESATAN model than it is done in EcosimPro. Whereas ESATAN is in principal a thermal node software directly using the finite difference method and therefore best suitable for such kind of heat transfer modeling, EcosimPro is the more complex and extensive tool, with which the detailing in connection of thermal nodes makes more effort, especially when an existing model needs to be extended. However, the main connections have been modeled with the same parameters and simplifications are made where they can be justified to not significantly impact the heat transfer.

Air Flow Modeling

Here the EcosimPro software is more suitable. The heat transfer coefficients to the air channel walls and the heat exchanger are calculated by EcosimPro from the geometrical details, parameters and physical properties of the materials. The ESATAN needs to be provided with separately determined coefficients. Slight differences between the ESATAN and EcosimPro parameters exist, e.g. the heat transfer coefficient at the walls of the air gap is calculated to about 23 W/(m²K) in EcosimPro, the coefficient used within the ESATAN program is 17 W/(m²K).

Also the humidity input, freezing on the heat exchanger fins and melting during the defrost periods could be modeled relatively easy with EcosimPro, which has been developed especially for ECLS and therefore already has features for dealing with humid air, that can be used here. The humidity is not regarded in the ESATAN model. This however can be justified because the condensing/freezing energy is negligible compared to the overall heat budget.

COMPARISON OF THE CALCULATION RESULTS

Several cases have been simulated to investigate the thermal behavior and performance of the RFR.

STEADY STATE OPERATION

Hot Case

The hot case is the worst concerning the insulation and cooling capabilities of the system. Table 1 shows the results of both models versus the requirements.

The calculation results are quite similar. The heat input to the lower Cold Volume is slightly higher in the EcosimPro model whereas the heat input to the upper Cold Volume is a little lower, resulting in a total difference of 9 W lower electrical Power consumption for the EcosimPro calculation. Correspondingly also the heat dissipation to the coolant loop is lower. The differences of the heat input into the Cold Volumes is due to the more detailed (but not necessarily more realistic) modeling of the conductive coupling to the rack established in the ESATAN model. This also explains the significant differences in the Cold Volume side panel temperatures.

Table 1: Hot Case Steady State

	Requirement / Bound. Cond.	EcosimPro	ESATAN
T_{Rack}	37 °C	BC	BC
T_{Cabin}	30 °C	BC	BC
$T_{cool, in}$ (low/up)	7.2 °C / -	BC / 10.8 °C	BC / 11.1 °C
$P_{ESS\ (incl.\ Fans)}$	80 W	BC	BC
T_{set}	/	-24.5 °C	-24.5 °C
T_{cargo}	< -22 °C	< -22.2 °C	< -22.9 °C
Heat load, upper	/	23.0 W	24.9 W
Heat load, lower	/	28.5 W	27.5 W
COP, upper	/	0.373	0.373
COP, lower	/	0.432	0.428
$P_{el, RFR, in}$	450 W	380 W	389 W
$Q_{dissipation\ to\ coolant}$	550 W	464 W	478 W
$Q_{cabin + rack}$	100 W	18.4+ 65.6 W	18.1+ 70.6 W
$T_{door, front}$ (up/low)	/	26.7/25.6 °C	26.3/26.2 °C
$T_{CV, side}$ (up/low)	/	27.0/27.1 °C	24.6/30.1 °C
$T_{post, min}$	/	30.7 °C	30.7 °C

Cold Case

The cold case is interesting with respect to condensation on the external surfaces. Of main interest are here the rack posts, which are interfacing to the Cold Volume side panels and directly contacting the face to cabin bearing the risk for condensation during phases with high cabin air humidity. Table 2 shows the results of both models versus the requirements.

Again the same tendency of deviations from the ESATAN to the EcosimPro model is seen, but less distinctively due to the lower difference between ambient and Cold Volume internal temperatures.

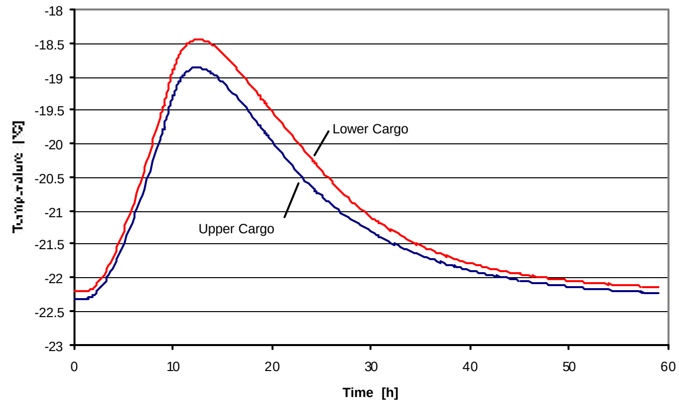
Table 2: Cold Case Steady State

	Requirement / Bound. Cond.	EcosimPro	ESATAN
T_{Rack}	13 °C	BC	BC
T_{Cabin}	15 °C	BC	BC
$T_{cool, in}$ (low/up)	7.2 °C / -	BC / 9.6 °C	BC / 10.0 °C
$P_{ESS\ (incl.\ Fans)}$	80 W	BC	BC
T_{set}	/	-24.5 °C	-24.5 °C
T_{cargo}	< -22 °C	< -22.2 °C	< -22.9 °C
Heat load, upper	/	17.5 W	18.0W
Heat load, lower	/	19.3 W	19.0 W
COP, upper	/	0.381	0.381
COP, lower	/	0.436	0.432
$P_{el, RFR, in}$	450 W	292 W	298 W
$Q_{dissipation\ to\ coolant}$	550 W	341 W	350 W
$Q_{cabin + rack}$	100 W	13.2+ W	13.0+ W
$T_{door, front}$ (up/low)	/	12.4 / 11.5 °C	12.2 /11.8 °C
$T_{CV, side}$ (up/low)	/	6.9 / 6.7 °C	8.0 / 5.6 °C
T_{post} (up/low)	/	9.4 °C	9.0 °C

PASSIVE PERIOD AND RECOVERY

During transfer of the MPLM from shuttle to ISS or back the power supply is switched off for maximum 8 hours with ambient temperatures may increase up to maximum 49 °C during this period. Calculating this scenario results in a maximum cargo temperature of -21 °C in ESATAN (starting from -22.2 °C steady state) versus up to -18.5 °C (starting from -22.9 °C steady state) in EcosimPro. After switching power on again (with ambient temperatures going back within 1 hour, the cargo reaches a temperature of below -22 °C within 25 hours (ESATAN) respectively 40 hours (EcosimPro, see figure 4). Although the general heat input into the Cold Volume is slightly lower in EcosimPro (i.e. better insulation capability of the Cold Volume walls), the cargo cools down faster when the cooling air flow is stopped, possibly due to better thermal coupling of the cargo to the drawer side panels. This leads to increased cargo cooling capability of the air flow, but also increases heat input over the side insulation panel walls via rails, air gap and radiation as well as over the air gap when the cooling air flow is stopped. A further tuning of these couplings should bring the results of the two models closer together. A better coupling of the cargo to the side panels of the drawers in EcosimPro would also explain the higher cargo temperature in the steady state cases (at same temperature set point and lower heat input from ambient).

Figure 4: Cargo Temperature with Passive Phase of 8 Hours

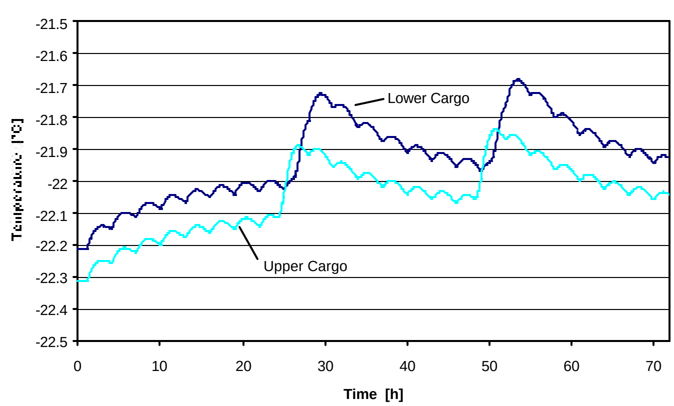


(EcosimPro)

DOOR OPENING

The worst case specified for the door opening scenario is one opening for 30 seconds every 3 hours. As worst case simultaneous opening of upper and lower Cold Volume is investigated with replacing the complete Cold Volume internal air by cabin air with 70 % relative humidity. In addition convective heat exchange with 1 W/(m²K) as well as radiative heat exchange with the inner surfaces seeing environment is simulated. During the door opening the air flow is stopped to avoid unnecessary heat losses. Both models show similar behavior, with cargo temperature increase to around -22 °C. The result of the EcosimPro calculation is shown in figure 5.

Figure 5: Cargo Temperature with Door Opening (EcosimPro) every



3 Hours and Defrost Period after 24 Hours.

Additionally the impact of the defrost period of 30 minutes power switch off once per day is seen, increasing the cargo temperature by about 0.3 K. But since the defrost should be performed during sleep time of the crew, the maximum cargo temperature in nominal operation should not significantly increase above -22 °C.

ASSESSMENT OF THE ECOSIMPRO SOFTWARE TOOL VERSUS THE ESATAN SOFTWARE TOOL

The EcosimPro software tool is a very complex tool to be used for various applications in the field of thermodynamic and fluid systems. ESATAN is a pure thermal analysis tool, which has been extended with FORTRAN subroutines to allow full RFR operational simulation. Both tools are in principle suitable for the thermal modeling of the RFR.

The thermal modeling approach is based on the same laws of heat exchange and therefore the results from the ESATAN and the EcosimPro model are quite the same. Differences occur due to different details when modeling the thermal conductors/radiators and for the modeling of air flow specific heat transfer coefficients which are done within EcosimPro, and directly adjusted according the corresponding variation of boundary conditions (e.g. due to variation of physical conditions with temperature), whereas in the ESATAN model an external calculation is necessary with corresponding data required as input.

The EcosimPro internal solver routines for non linear equation systems are significantly reducing the programming work, whereas ESATAN requires self programmed subroutines for the solution of the equation systems. Also the convergence of the model and quick finding of the steady state could be realized better due to the EcosimPro specific tracing to failure resolution and optimization of starting parameters.

With respect to the modeling of the nodes and connection with thermal conductors the work with ESATAN is easier, optimization of a model by improving the details can be established more quickly with ESATAN specifically designed for this kind of thermal calculation.

A further advantage of EcosimPro is the possibility of direct plotting the calculation results, so that the development of the parameters can be followed also during a long duration transient simulation. The resulting plot can then be further processed and transferred to the reporting document. EcosimPro has also a post-processing utility which permits to plot any variable or data of a calculation (the results being saved at each time step in a binary database).

CONCLUSION

Two thermal model of the Crew Refrigerator/Freezer Rack have been established, using the ESATAN and the EcosimPro software. Different reference load cases for the RFR have been studied to compare the performance simulation with the two models. In general the results are well comparable and only slightly deviate due to different detailed modeling the thermal connectors.

In general it can be stated that EcosimPro is well suitable for the thermal modeling of this kind of application and can be efficiently used for detailed design and optimization purposes.

ACKNOWLEDGEMENTS

The development Phase B/C0 on the ISS Refrigerator/Freezer Racks as well as the actual study is performed under ESA contract 13490/99/NL/JS. We would like to thank especially Mr. Di Palermo, as ESA's project responsible technical officer and Mr. Pin, being responsible for the study presented here for their unique support during the project.

REFERENCES

1. RFR Thermal Analysis Report, RFR-RP-AST-1009, Issue 1, 30.06.2001
2. ESTEC Internal Working Paper EWP-2038, Simulations on the Refrigerator Freezer Rack using Ecosim Software, TOS-MCL\2715\HB, July 1999.
3.

DEFINITIONS, ACRONYMS, ABBREVIATIONS

BC	Boundary Condition
COP	Coefficient of Performance
CV	Cold Volume
MPLM	Multi Purpose Logistics Module
RFR	Refrigerator Freezer Rack
TEC	Thermo Electrical Cooler

CONTACT

Roland Müller
Astrium GmbH,
Space Infrastructure Division
Dept. IO44
88039 Friedrichshafen (Germany)
Email: Roland.RM.Mueller@astrium-space.com

ADDITIONAL SOURCES

EcosimPro is a product developed, maintained and distributed by Empresarios Agrupados International, Spain, under an ESA Contract. Information is available on the Web site http://www.ecosimpro.com.

ESATAN is a product developed, maintained and distributed by Alstom Power Technology Centre, UK, under an ESA Contract. Information is available on the Web site http://www.techcentreuk.power.alstom.com.

Contact at ESA for ESATAN and EcosimPro: Olivier.Pin@esa.int