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High Temperature Gas Reactor Component Test Facility Mission Needs and Requirements

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AREVA

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1. Mission needs

A large helium test loop, the Component Test Facility (CTF), providing representative conditions in terms of temperature, pressure, fluid flow and chemical environment will be necessary from the selection of design options to the qualification of NGNP components and for subsequent commercial HTR applications. The needs for tests have to be precisely identified in order to define the specifications of the loop.

Moreover test needs will spread out over time, from very short term preliminary tests for selecting options for the design of components during the conceptual design phase to component qualification and later to test needs in case of operational problems / troubleshooting on NGNP or in support of future commercial plants. On the other hand, some of the components and technologies of the large helium loop will certainly not be off-the-shelf and will require special development tests before finalizing their design and qualifying them for operation in the loop. Therefore when defining test needs the development phase when the CTF will absolutely be necessary will have to be determined, while early needs for NGNP design and for the development of the loop itself might be addressed in other facilities that already exist or that can be developed within a short delay.

1.1 Review of CTF needs

1.1.1 Needs for NGNP development

1.1.1.1 Component testing

The most important mission of CTF is the qualification of reactor components and major support systems. Depending on the type of component and the novelty of the design, a final qualification in representative operating conditions should be sufficient or preliminary tests on simpler facilities should be necessary for supporting the selection of design options and for preliminary validation of the selected design. This part of the report specifies mission needs for NGNP CTF for each component as follows:

- For the ***Intermediate Heat eXchanger (IHX)***, tests have to address the thermal-hydraulic (heat transfer and pressure drop) performance, the thermo-mechanical behavior in steady state and transient conditions, flow induced vibrations and fouling. Endurance tests will have to be performed.
    - If a tube design is selected, there is sufficient experience from past programs to limit the testing to the final qualification in a large helium loop at full scale for the tube length, if not for the tube number, and for the collector. It should be noted that for HTTR, which is only a small scale test reactor, it was even considered that the large scale test of the IHX, which was initially planned on the HENDEL helium loop, was not really needed and therefore that the IHX could be set up on the reactor only after elementary tests (creep collapse and creep-fatigue of tubes, thermo-hydraulic and seismic behavior of the tube bundle, development of in service inspection technique of the tubes). This was not the case for the German PNP project, for which extensive tests

of the IHX needed for industrial process heat applications have been performed in the KVK loop.

- If a plate IHX is selected, at least for the hydrogen production loop of NGNP, as there are several very different options for plate design (machined plates (HEATRIC type), plate-fin concepts, stamped plates) preliminary tests should be performed during the conceptual design phase in order to select the most appropriate concept in terms of thermo-mechanical behavior in high temperature steady state and transient conditions and in terms of thermo-hydraulic performances. As CFT will not be available yet during this early phase, a step by step approach is recommended as follows:
    - Separate effect tests should be performed first in different simple loops, each one providing only one type of representative conditions. The merit of this approach is not only to allow very early tests in existing facilities, but also to allow studying separately the influence of the different operation conditions on the behavior of the IHX, which will make optimization of the design easier.
    - A first step of integration of most of the representative conditions (all, but not the helium flow rate) can be considered in a medium size loop with a lower power than in CTF (a power of the order of 1MW would be sufficient). It could be built rather early and would allow verifying soon that the trends shown for instance in air loops are verified in helium at that no unpredicted effect follows from the superposition of the different operating conditions studied separately in the first step. The interest of such a loop is also to enable to qualify CTF components in representative conditions and to become acquainted with technologies of helium circuitry first in a flexible facility at relatively low scale, limiting the risks of erroneous design and poor performance of CTF.
    - Then CTF would be used for the final qualification of the IHX.

It should be noted that fouling tests by solid particles should probably be considered in a dedicated facility in order to avoid contaminating the loop with species that could modify in an uncontrolled way the chemical environment in the loop and possibly lead to degradations of some of its components.

- For a ***steam generator***, the test needs are rather similar to the needs for a tube IHX, with a secondary side in water. In particular the following issues will have to be addressed: thermal hydraulic performance for helical coil type tube bundle, structural integrity of high temperature parts, such as super heater and re-heater tubes and headers.
- The ***circulators and the helium turbines and compressors of direct cycle*** are generally tested in air by their manufacturers, who have appropriate facilities for that purpose. But qualification in helium is necessary and requires a scale as close as possible from full scale, which requires very large flow. This is a particular concern for the large helium turbines, which requires a very large test loop in helium operated at high temperature. In Germany, the EVO loop, designed for testing a turbine for a 600 MW reactor, had a designed power of 120 MW. In operation it could not actually exceed 50 MW, which illustrates the difficulty of being sure of the performance of components without tests performed in helium atmosphere. A possible solution for large helium turbines could be to

have the final qualification of the turbine in the prototype reactor itself. For the circulator of a 4 loop 600 MW reactor, the final qualification on CTF can be considered more easily. It should be mentioned that before final qualification on CTF, the dynamics of the circulator rotor supported by magnetic bearing, as well as the behavior of catcher bearings should be tested at a dedicated facility.

- It will be necessary to test the behavior of the ***fuel and reflector graphite blocks***: heat transfer performance (including with possible channel blockage) in steady state and transient situations, pressure drop, by-pass flow and flow induced vibrations will have to be addressed.
- The thermal-hydraulics of ***core inlet and outlet plenums*** must be studied carefully: the core inlet plenum flow conditions the homogeneous feeding of the different parts of the core and a good mixing of cold bypass streaks with the hot helium leaving the core must be obtained in order to avoid inducing thermal fatigue on the downstream structures (in particular the hot duct thermal barriers) due to large temperature fluctuations. The drivers for homogenizing the helium temperature are the turbulent mixing and, in the outlet plenum, the heat transfers between hot and cold helium. For the outlet plenum, an isothermal mixing test is therefore not sufficient and large mass flow rate tests with the possibility of mixing cold gas with heated gas should be considered, not necessarily in helium, which would lead to too large flow rates, but in air.
- For ***the thermal barrier of the hot gas duct***, tests should address the thermal performance, the vibrations induced by the flow and the circulator, as well as the behavior in a fast depressurization accident. The key parameter to be reproduced at full scale is the fluid velocity. The design of the whole duct should be reproduced in the test section, including the fixation system and the transition zones at the connection with the reactor and IHX or turbo-compressor vessel.
- For ***valves, check valves and rupture disks***, leak tightness, vibration and material resistance tests are needed. For the isolation valves at the secondary inlet and outlet of the IHX, large scale tests will be required.
- For the selection and qualification of ***materials*** for NGNP components, the behavior of candidate materials in high temperature conditions should be addressed: in particular ageing, creep, creep-fatigue and corrosion properties should be characterized through test performed on dedicated small scale facilities with standard material specimen. In particular, corrosion studies in impure helium atmosphere can be performed in small loops at atmospheric pressure, with a very precise control of impurities, as it appears that the significant parameters are their partial pressures. Nevertheless it is important to check that the total pressure does not affect the results obtained on these loops and therefore, materials testing should be possible in the medium size loop if available before CTF, or on CTF itself. For that purpose the helium atmosphere of these loops must be controlled with the possibility of keeping a representative content in impurities. Moreover the final qualification of components in CTF will allow verifying that materials behavior first acquired on small samples are confirmed for large parts.

  On the other hand for materials of the reactor vessel and of its internal structures (metallic materials for the vessel and for part of the internal structures, ceramic materials for other internal structures (graphite in particular for fuel and reflector blocks and composites for control rod claddings), the impact of irradiation on material properties must be addressed. This is in general done through irradiation of samples in a material test reactor (MTR) and post irradiation tests for characterizing the high temperature behavior of the irradiated samples. But in some cases the decoupling of the irradiation and of the characterization of materials behavior under mechanical loads and chemically aggressive environment is not possible: in particular for graphite, creep is significant only under irradiation and therefore irradiation tests have to be performed on stressed samples. The possible impact of irradiation on corrosion properties of reactor vessel and in-vessel materials should also be assessed. For that purpose, an in-pile corrosion loop is needed.

Erosion of materials by dust should also be addressed in a dedicated loop where significant quantities of dust can be injected (same as the one used for IHX fouling tests).

- The performances of the ***helium purification system*** can be tested on the helium purification system of CTF, or even on the purification system of a medium size helium loop, if available before CTF. As all the materials of the reactor primary circuit (most particularly graphite) will not be found in the helium loop, some of the impurities, which cannot be avoided in the atmosphere of the reactor (CO, CO_2, CH_4, graphite dust...), will not be spontaneously present in the loop. Therefore injection of these impurities must be planned in CTF, in order to get a representative chemical environment. Contrary to gaseous impurities, which will be homogeneously distributed in the coolant, dust distribution will probably vary depending on deposition and lift-off mechanisms, which have no reason to act in the loop in the same way than in the reactor, as the loop circuit will certainly not be fully representative of the reactor primary circuit (see 1.1.1.3). Therefore contrary to gaseous impurities, the injection of dust in the loop is questionable: while the gaseous impurities can be easily removed from the loop by the purification system and their quantity in the circuit of the loop fully controlled, this is not the case for the dust that would generate a durable pollution of the circuit, with a distribution that cannot be controlled and that has no reason to be representative of the reactor case.
- Friction and wear of ***sliding parts*** in representative helium environment must be addressed. This includes as well quasi static situations (thermal expansion), as vibrations and translations (CRDM). In a first step, sliding tests of couples of simple surfaces of different materials and coatings can be performed in tribometers with high temperature and representative helium atmosphere, but finally during the qualification of components in which the sliding surfaces will be represented with their actual geometry, representative relative movements of these surfaces should be ensured.
- ***Static, dynamic and possibly rotating leak tightness devices*** should be tested in helium. As very limited flow is involved, these tests can be performed on dedicated test benches.
- ***The CRDM and the fuel handling machine*** for a prismatic block core or ***the pneumatic fuel handling system*** for a pebble bed core should be qualified at full scale in helium atmosphere, with the actual flow feeding all parts of these systems (including the flow in the graphite block channels where control rods are introduced), which is rather small. Their reliability will be demonstrated from the repletion of a large number of operating cycles.

- As CTF will provide all representative conditions of HTR operation, except radiation, CTF can be used for the development and the qualification of all the ***instrumentation*** required for NGNP, except the core and internals instrumentation. But instrumentation tests can be performed as well in a smaller helium loop and will anyway have to be performed in such a loop for the development and qualification of CTF instrumentation.

1.1.1.2 Code qualification

There is another type of needs to be satisfied by CTF: the needs related to qualification of computer codes used for thermo-fluid dynamics calculations and fluid structure interactions in NGNP. The codes are of two types, the CFD codes calculating the detailed 3D flow configuration in a component and the system transient analysis codes:

- For CFD codes, the possibility for CTF to provide sufficient flow rate to receive large representative mock-ups (e.g. core inlet and outlet plenums) and the possibility to have a sufficiently detailed measurement of the flow distribution in the mock-up and not only measurement of the global characteristics of the flow are prerequisites for CTF to contribute to CFD code qualification, which will anyway also use simpler test facilities with easier measurement of the distribution of the fluid flow, like the MIR facility at INL, even if the fluid flow obtained in such facilities (isothermal flow) is less representative of the reactor conditions than in CTF.
- The system transient analysis codes can be qualified through benchmarking with measurements of global fluid flow parameters (pressure, flow rate, temperature...) from operational transients of various loops and reactors. CTF can add new data to a large collection of already existing data (see Part 2). For the qualification of codes for NGNP safety demonstration, should it be required from CTF to be fully representative of NGNP configuration and not only to provide representative conditions in test sections? Contrary to the case of LWR systems, the modeling of the fluid flow coupling the components being quite simple in a HTR (modeling of an ideal gas), the quality of the system behavior simulation with such codes will mainly depend on the quality of the modeling of each component, which will be validated by testing these components on the CTF loop (which will therefore have to provide all type of normal and abnormal operating conditions for all reactor components). Therefore the verification that there are no significant discrepancies between calculation and measurement for many different steady state and transient situations of several very different system configurations should be sufficient for qualifying a system transient analysis code, without necessarily having a validation with a loop fully representative of NGNP. The fact that calculations performed until now with system transient analysis codes for various situations have always shown very good agreement with experimental results comforts this approach, which should of course be endorsed by safety authorities. If a representative loop is nevertheless needed for validating the calculation of the coupling of the different components of the HTR system, it will not necessarily be CTF: it can be a smaller loop with possibly another fluid than helium. This was the case for the South African micro-turbine operated with nitrogen as the working fluid and used for validating the calculation of the PBMR direct cycle system behavior with a complex multi-shaft turbo-compressor.

- It should be noted that, as long as thermo-fluid dynamics modeling has to be coupled with the modeling of other phenomena (graphite corrosion during air ingress, reactor physics), the coupling of models must be qualified in a dedicated facility (for instance a loop like the NACOK loop for air ingress and a test reactor for coupling core fluid flow modeling with reactor physics modeling). For fission product transport, a dedicated loop that could be contaminated could be considered if the large uncertainty existing in present modeling is not acceptable and the appropriate measuring techniques should be defined and if necessary developed for studying transport, deposition and lift-off in NGNP itself.

1.1.1.3 Component testing loop or global system loop?

Designing the whole of the CTF facility to be fully representative of NGNP would create additional constraints. It would decrease the flexibility of the loop to changes in the system design (in particular for long term evolutions for the commercial reactors beyond NGNP) and would certainly increase its cost.

Even if it does not impose limitations in the testing of components, it is clear that the choice of only providing representative boundary conditions on test sections for components, instead of building a loop fully representative of the whole NGNP system, will preclude or limit the possibility for the loop to address some missions:

- The loop cannot be used for developing procedures and for training and qualifying the operators for NGNP, as the loop will not have the same natural behavior (in particular not the same thermal inertia) as NGNP. Developing procedures and qualifying operators are usually performed on a simulator, which will also have to be developed for NGNP.
- Preparing maintenance, repair and component replacement programs will have to be made on full scale mock-ups representative of the configuration of the local environment of the part to be maintained or repaired and not on a loop which will not reproduce the geometry of the reactor.
- Would fission product be introduced in the loop for assessing contamination transport, deposition and lift-off deposition, results would not be representative of the situation in the reactor: with the usual 8 shape configuration of this type of loop, there is a region of the loop much colder than any part of the primary circuit of the reactor, which might be a trap for fission products. Anyway contaminating the loop by providing an interface with NGNP or by introducing active components would make any intervention on the loop complicated and would no more allow a flexible use of the facility. Radioactive contamination of the loop should therefore be avoided.

1.1.2 Other Needs

If innovative or even evolutionary components are introduced in ***future commercial HTR/VHTR plant***, the same process of testing will be required for selecting design options, assessing their potential and finally qualifying them. But contrary to NGNP, CTF will be available right from the beginning of the development, which will allow directly testing the new components in fully representative conditions if reactor operating conditions do not exceed too much those of NGNP. Nevertheless for optimizing the design of very innovative components, preliminary separate effect elementary tests might still be useful.

The LWR experience shows that a loop like CTF can also be very useful for ***diagnosing operational problems***, for instance unexpected vibrations, wear of fatigue issues, by trying to reproduce the phenomena in the loop. Now, apart from the wish not to contaminate the loop for keeping its flexibility and easy access, if the problems affect large components, it is clear that it is only mock-ups of these components at a reduced scale, not the concerned components themselves, that can be received in the loop, which does not provide the full helium flow rate of NGNP.

CTF can provide representative conditions to an IHX or a steam generator, with a reduced power compared to NGNP. Therefore it can act as a heat source for ***testing process heat applications*** that could be coupled with NGNP or future commercial plants (hydrogen production, coal to liquid, steam for oil sand extraction, etc.). It can be used up to the final qualification of these processes before coupling them to the reactor only if the power scaling conditions are considered to be representative for that purpose.

1.2 Categorization of needs

In table 1, the needs of tests for NGNP are distributed following the different design phases when they are needed:

- A step-by-step approach was already proposed for plate IHX, with elementary separate effect tests as early as possible. Such approach is absolutely necessary for this component, not only because it is a challenging component for which early experimental verifications are necessary for checking that there is a chance for it to withstand HTR operating conditions, but also because experimental support is needed for selecting the most appropriate design between different plate IHX concepts. This approach is also recommended for other components in order to minimize the risk to meet snags in a late design phase. For the components which benefit from a sufficient experience feedback from past developments (e.g. the tubular IHX), the step-by-step testing program could be bypassed and going directly to qualification on CTF can be considered.
- It is also recommended to develop a medium size loop for an intermediate step, not only for being able to perform more representative tests of the plate IHX without waiting for the availability of CTF, but also in support of the development of CTF. It should be added that this loop could even be used for qualification of components that do not require a large helium flow rate (CRDM, fuel handling system, reflector graphite blocks, instrumentation…).
- CTF should therefore be dedicated to the qualification of components that require a large helium flow rate. This is enough for keeping the loop fully busy for several years as the qualification will include long duration endurance testing (for instance the HENDEL loop was operated for about 23 000 hrs, even if the test program was more limited than the one which should be considered for NGNP – in particular there was no test of the IHX). In order to shorten the period of time which will be necessary for finalizing all the qualification tests, it should be possible to perform parallel tests in secondary circuits of the loops. Nevertheless as most of the tests will include transients and cycling, the interaction of the different circuits will probably limit the possibility of performing parallel tests. Therefore benefiting from an additional independent loop where part of the

tests which do not require large flow can be performed will provide an asset of flexibility in the management of the qualification program.

- It should be mentioned that in some cases (turbo-compressor for direct cycle, system transient analysis code, tests involving dust injection or radio-contamination of the loop circuit), CTF could be considered not to be appropriate for qualification and that additional dedicated loops might be considered. In some cases (tests of the turbo-compressor in helium, qualification of the transient analysis codes), alternative paths could be considered for avoiding such additional investments.

Table 1 also provides, with different colors, the level of priority of the different tests: absolute priority (red) should be given to the qualification tests, either in CTF or in other loops. Without such tests NGNP could not be licensed and constructed. Early tests needed for the selection of design options have also an absolute priority because the project could not continue without getting their results. Some other early tests, needed for confirming the feasibility of some design options, should be given a high priority (yellow). If they are not performed, snags could be discovered when performing the final qualification, with risks of important delays. None of the other tests should be considered with a low priority, because all of them are meant at reducing the risk of a late discovery of issues than could lead to delays in the project: they should be given a medium priority level (green).

Table 1: Test needs in the different NGNP design phases

		Conceptual design		Preliminary design	Final design
IHX	Tube IHX				Qualification in CTF
	Plate IHX	Heat transfer	Influence of the nature of the gas: test in single tube geometry	Intermediate step recommended: test in a medium size He loop (~ 1 MW) where all representative conditions exist but where the flow rate is not sufficient to test a large enough mock-up to have a representative flow distribution in the headers	
			Influence of IHX channel geometry: test in air or He with a few plate mock-up with representative channel geometry (not necessarily full temperature)		
		Pressure drop: on the available loops in air or He			
		Thermo-mechanical behavior: can be performed in an air loop, where the air circulating in a representative mock-up is heated to operating temperature and where representative thermal transients can be performed			
		Distribution of flow to the different plates from the header			
	Fouling tests				Tests in a dedicated facility with possibility of dust injection
Steam generator					Qualification in CTF
Circulator		Magnetic and catcher bearing testing		Tests in air (manufacturer facility)	
Turbo-compressor (direct cycle)		Magnetic and catcher bearing testing		Tests in air (manufacturer facility)	Dedicated He loop (> 100 MW)?
Fuel elements					Qualification in CTF
Internal blocks				Preliminary tests in medium size He loop, in particular for estimation of bypass flow rate	
Inlet core plenum				Test possible in cold dedicated mock-up in air or liquid with large flow	
Outlet core plenum		Isothermal tests in MIR facility		Test in dedicated mock-up with large air flow, part of it being heated	
Hot gas duct		Initial testing in He test bench for thermal performance of the thermal barrier and behavior in depressurization accident at least for hot duct of medium size helium loop and CTF			Qualification in CTF
Valves, check valves and rupture disks					

Table 1 (continued): test needs in the different NGNP design phases

	Conceptual design	**Preliminary design**	**Final design**
Materials	Elementary tests for characterizing high temperature behavior (ageing, creep, creep-fatigue, corrosion…). Required test facilities: • Standard material laboratory equipment • Low pressure He loops with controlled impurities for corrosion studies • Irradiation reactor • In reactor He loop, for influence of irradiation on corrosion behavior	• Additional tests on large scale representative parts • Verification of corrosion behavior at high pressure in the medium size He loop	Integrated in component qualification in CTF
		Dedicated test facility with the possibility of dust injection for erosion testing	
Sliding parts	Initial testing in He tribometers		Integrated in component qualification in CTF
Leak tightness devices	Initial testing in He test bench		
CRDM			Qualification on full scale mock-ups fed by representative He atmosphere from CTF or from the medium size He loop
Fuel handling system			
Instrumentation		Qualified on the medium size He loop	
CFD code qualification	Validations on representative mock-ups in other fluids than hot He		Qualification in He on CTF
System transient analysis code qualification	Qualification through benchmarking on tests in different loops with different configurations	Additional data for benchmarking from tests on the medium size loop	Additional data from benchmarking from tests on CTF
Qualification of coupling fluid dynamics codes with reactor physics codes	Code to code benchmarking		
	Benchmarking with experimental results: Depends on the availability of in core flux and temperature measurements		
Qualification of the coupling of fluid dynamics codes with graphite corrosion modeling (air ingress calculation)	Tests on a dedicated loop		
Qualification of fission product transport modeling		Tests on a dedicated loop?	

2. Justification

2.1 *Existing facilities*

2.1.1 Tests facilities for preliminary tests

Beyond standard materials laboratory and hot cell equipment and MTRs, specific facilities that can be used for preliminary tests of NGNP are presented in Table 2. Most of them are those existing or planned in Europe, in support of the ANTARES program of AREVA or used in the program for development of HTR technology funded by the European Commission. Such facilities certainly also exist in other countries, but it is difficult to have an exhaustive view on them.

2.1.2 Large helium component test loops

The characteristics of past, present and planned large helium loops in the world are summarized in table 3. There are two types of qualification tests needed for components, with two types of loops used for these tests:

- The tests for which the need to keep representative conditions requires a flow rate close to the full flow rate in the reactor primary loops: this is the case of the turbines for direct cycle reactors or for the largest circulators considered for indirect cycle systems (with steam cycle or gas cycle in the secondary circuit). This is also the case for the big isolation valves on the secondary IHX inlet and outlet. For avoiding significant flow pattern distortions in the test, it is recommended not to reduce the component dimensions in the test mock-up by a factor exceeding 3 to 5, which corresponds, for the flow rate to a downscaling factor which should not exceed 3^2 to 5^2. If possible, the down-scaling should even be lower than these limits. Therefore for qualifying the hydraulic performance of big turbo-machines and secondary isolation valves, dedicated loops with large flow rate have been used in the past. A solution chosen for PBMR is to use the component testing loop, boosting the helium flow rate during a short period by the discharge of a large pressurized helium tank.
- For the other components, representative mock-ups can generally be defined without requiring full flow rate: for instance for tube heat exchangers, a full scale component with a reduced number of tubes can be used, and for plate heat exchangers which includes several dozens of plate modules, the testing of a single module with its headers is sufficient; for the hot gas duct, a cylindrical plug can be put in the middle of the channel, allowing keeping a representative helium velocity in a sufficiently large annular space at the contact of the thermal barrier with a reduced flow. As qualification tests should not only address thermo-hydraulic, but lifetime performances of the components, the loop should not only provide representative conditions in terms of temperature and flow distributions in the mock-ups, but also for all the factors that can affect the component lifetime (vibrations, mechanical and thermal cycling, impure helium atmosphere with the same impurities as in the reactor with same proportions).

2.2 Assessment of ability of existing facilities to meet needs

A large part of facilities similar to those identified in table 2 for preliminary tests certainly already exist in the US or can be made available within a short delay from upgrading existing facilities. Nevertheless for a few unique rather complex facilities, like the NACOK air ingress loop of the Jülich Research Center, or the magnetic bearing testing facility FLP 500 of IPM Zittau, an alternative to duplication of such facilities in the US would be to perform the tests required for NGNP in these facilities, which would allow directly benefiting from the large testing experience of the teams operating them, probably bypassing years of learning for teams starting new facilities. In other cases, for instance for corrosion of NGNP materials in impure helium atmosphere, even if corrosion loops are presently established in US laboratories, considering the wide scope of materials (including their variability) and test conditions to be explored, as well as the length of each test, sharing the test program with teams involved in similar research in other countries could be beneficial for progressing faster.

For the large component testing helium loop, the situation is rather different: it appears that there is no loop presently operated or planned with a sufficient power for the qualification of NGNP components (see Part 3 for the functional & operational requirements for CTF). Even if compromises are looked for in order to accept tests at a reduced scale or if the NGNP power is reduced, the situation does not change significantly: the availability of the two loops which have a sufficient power to be considered, the OKBM CT-1312 loop and the FZK HELOKA loop is questionable:

- CT-1312 is a 17 years old loop; it is no more operated and it has been put in prolonged storage. It is difficult to know in which condition are its components, how long it will take to restore and restart the loop and how many competent operators could be available quickly for restarting.
- HELOKA is developed for the needs of the fusion program. The temperature is not sufficient for testing the highest temperature components of NGNP. The possibility of addressing HTR needs including by adding a high temperature branch to the loop for has already been investigated (Fig. 21) and there are provisions in the hall which will shelter the loop for receiving such a branch. Nevertheless the loop will not have any system for helium purification and for injection of impurities (except if it is specially developed for HTR needs), which limits the use of the loop to performance testing, excluding endurance testing. Moreover the loop will be mainly used for fusion needs and the FZK team developing HELOKA thinks it could be made available for HTR tests only 1/3 of the time.

Even if it does not seem reasonable to rely on these loops for NGNP development, possibilities of using them as a back-up or complementarily to CTF for some tests which require a limited flow rate could be investigated. The same could be done with HELITE, if the decision for building is taken.

This report also recommends having as soon as possible a medium size loop available, for early tests before having the possibility to use CTF and for supporting the development of CTF itself. One could think about using HELOKA or possibly HELITE for this first step. But one of the main objectives of this first helium loop, which is to get acquainted with helium technologies before implementing them at large scale on CTF, would be missed if such a solution is chosen. A possible solution, in order to shorten the design phase of the loop, would be to start from HELITE configuration, as the requirements for the ANTARES program, which were the baseline for establishing the design of this loop, are rather similar to NGNP requirements.

Finally, the needs for thermo-hydraulic qualification the turbo-machines of NGNP and further commercial HTGR are strongly depending on the design options for the power conversion system:

- If direct cycle is selected, as helium turbines are rather challenging and cannot be easily extrapolated from industrial turbines, it should be recommended to avoid being at the lower limit of possible downscaling and a mass flow rate of at least 30 kg/s should be necessary. Moreover helium should be heated to full operating temperature of NGNP. The power of the loop should be at least about 80 MW, which is not in the range considered for NGNP (see Part 3).
- If indirect cycle is selected with a single primary loop and therefore a single circulator, this circulator being beyond present industrial experience (~ 15 MW), one should also be cautious not to downscale too much the qualification test mock-up and therefore similar flow rate as for a helium turbine is needed, but with a lower operating temperature (400-500°C), and therefore the required power of the loop (40-50 MW) is lower than for turbine testing, though still higher than the power needed for testing other components.
- If indirect cycle is selected with several primary loops (which is necessarily the case if a tube design is chosen for the IHX), the power of the circulators remains within industrial experience and the flow in each loop is of course lower. Qualification tests could therefore be easily performed in CTF.

For the secondary isolation valves, the fluid might not be helium. If a fluid similar to the one selected for ANTARES secondary circuit (80% N_2, 20% He) is used, tests in air can be considered as representative enough.

Now for the turbo-machines and possibly isolation valves, which strictly speaking would require qualification with higher flow rate tests than provided by CTF, a compromise solution can be proposed, which avoids the development of an additional very costly loop:

- Full power tests in air,
- Reduced power tests in CTF, including performance and endurance tests,
- Possibly adding a pressurized helium tank for performance tests through the discharge of this tank (this would not allow addressing endurance behavior but at least, for turbo-machines, the higher risk, which is that their actual power in the reactor is lower than the design power, forcing to reduce the reactor power – as shown by the difficulties met in the past German HTR program for the turbine development (with in particular the impossibility to reach in the EVO loop more than 42% of the design power of the turbine)).
- Final qualification planned in NGNP start-up tests.

2.3 Summary of recommendations

As there are very few large helium loops in operation or planned, as their availability for NGNP is uncertain due to age and present status of prolonged storage, or on the contrary to large mobilization for other programs and as they could not anyway address all test requirements for NGNP (insufficient flow rate or temperature, absence of system for controlling the impure helium chemistry), the risk for missing justifications for NGNP licensing would be high if a dedicated loop, fully addressing NGNP test requirements is not built. Therefore **AREVA NP strongly recommends the construction of CTF loop.**

The maximum temperature in at least one test section of the loop should be the maximum operating temperature of the reactor. The maximum flow rate will be determined (see part 3) as the flow rate needed to have representative tests with component mock-ups – to be studied case by case for each component. The loop power will be derived from the required temperature and flow rate.

From past experience it appears that a power of at least 10 to 20 MW will be necessary. In case of direct cycle or indirect cycle with a single loop, the needs for turbo-machines and secondary isolation valves would even require much higher power. Nevertheless for these components, it is recommended to consider compromise solutions, which would allow getting confidence in their operational behavior, while avoiding the construction of a huge loop of 50 to 150 MW only required for testing them.

It is also recommended to construct, before CTF, a smaller helium loop, which would allow early familiarization with helium technologies before implementing them at large scale in CTF, minimizing the risk of having to face major delays due to failures, underperformance, etc. when commissioning CTF, moreover providing to NGNP development program the benefit of early helium tests minimizing the risks of missing some important issue, when selecting in the early NGNP design phase some of the base design options, and finally adding some flexibility in the helium testing capabilities for components that do not require a high flow rate.

Finally, even if it should be avoided relying only on facilities existing abroad, a large international cooperation is recommended not only for helium loops but also for other test facilities. Such cooperation would bring some flexibility in the test program and would allow accelerating it by possibly transferring some tests in foreign facilities, knowing that anyway CTF will necessarily be kept busy during several years with tests for which representative conditions cannot be obtained in any other facility. Moreover some of the foreign facilities could bring specific conditions that cannot be obtained in CTF (e.g. air ingress conditions with graphite), requiring expensive dedicated loops. The benefit that could be obtained from foreign experience for strengthening the expertise of NGNP test teams in helium technologies and in other testing techniques should also be taken into consideration.

Table 2: facilities meeting preliminary test needs for NGNP development

	Test need ##		Test facility	Status #
Plate IHX	Heat transfer	Influence of the nature of the gas: test in single tube geometry	Le Creusot AREVA Technical Center (Fig.1), He and He + N_2 mixture, tube geometry	Operational - Available
		Influence of the geometry of the IHX channels: test in air or He with a few plate mock-up with representative channel geometry (not necessarily full temperature)	CLAIRETTE loop: CEA Grenoble, low temperature air, current channel representative geometry	Operational - Available
			HE-FUS3 loop (Fig.2): ENEA Brasimone (Italy), He, 10 MPa, 510°C, 0.35 kg/s, 346 kW	Operational, limited availability (mainly used for fusion)
			HETL loop: INET, Beijing (China), He, 8 MPa, 400°C, 650 kW	Dismantled
	Pressure drop: on the available loops in air or He		In HE-FUS3 and CLAIRE	
	Thermo-mechanical behavior		CLAIRE loop (Fig.3): CEA Grenoble, air, 0.6 MPa, 950°C, 0.2 kg/s, 245 kW, representative thermal transient capability for ANTARES	Operational and Available at 510°C for recuperator tests. Ready to be up-graded to 950°C within a few months
	Distribution of flow to the different plates from the header		PAT loop (Fig.4): EdF Chatou, air, 1.5 MPa, room temperature, 1.3 kg/s, steady state operation	Can be operational and available within a delay of a few months
Plate and tube IHX	Fouling tests in a facility with possibility of dust injection			Dedicated facility to be defined
Circulator and direct cycle turbo-compressor	Tests of the circulator in air		Manufacturer facility	Operational – Availability is unknown
	Magnetic and catcher bearing testing		FLP 500 (Fig.5): IPM Zittau, dynamics of a rotor supported by active magnetic bearings, in air or He, up to 500°C	Operational – Available in air. Availability in He would require a limited delay.
Hot gas duct	Isolation thermal performance in normal operation and behavior during a depressurization accident		HETIMO (Fig.6): CEA Cadarache, He, 10 MPa, 1000°C, dP/dt = - 2 MPa/s	Operational - Available

Table 2 (continued): facilities meeting preliminary test needs for NGNP development

	Test need ##		**Test facility**	**Status #**
Materials testing	Corrosion loops in impure He atmosphere (beyond standard materials laboratory and hot cell equipment and MTR)	Uniform corrosion	CORALLINE (Fig.7): CEA Saclay	Operational - Available
			CORINTH (Fig.8): CEA Saclay	Operational - Available
			Le Creusot AREVA Technical Center (Fig.9), # 1000°C, # 36 Nl/h, impurities from ppm to %	Operational - Available
			ESTEREL (Fig.10): EdF Les Renardières	Operational - Available
		+ creep	CORSAIRE (Fig. 11): 900°C, 2 kN load cell, 15-20 Nl/h	Operational - Available
			FLAMENCO: CEA, creep at low stress by bending tests, 1000°C, 15-20 Nl/h, 20 MPa bending	Operational - Available
		+ low cycle fatigue and creep	LCF (Fig.12): CEA Pierrelatte, 1000°C, 10-100Nl/h, 35 kN tension-compression	Operational – Available
		+ radiation	Corrosion loop in the reactor LVR-15 (Fig.13): UJV Rez (Czech Republic), 7 Mpa, 500-900°C, 0.01 kg/s	Components are being manufactured. Operational in 2009 – Availability is unknown
Sliding parts	Initial testing in He tribometers		Le Creusot AREVA Technical Center	Operational - Available
			CEA Cadarache (Fig.14): 0.5 MPa, 1000°C, load 0-20 MPa, sliding 20 mm	Operational - Available
Leak tightness devices	Initial testing in He test bench		HETIQ (Fig.15): CEA Cadarache, 10 MPa, 500°C	Operational - Available
CFD code qualification	Detailed flow map in an obstructed environment		MIR test facility: INL	Operational - Available
System transient analysis code qualification	System loops with different configurations		HE-FUS3	Operational, limited availability (mainly used for fusion); some transient tests have been performed
			Micro-turbine loop (South Africa): N_2 Brayton cycle with multi-shaft turbo-compressor	Operational; test results available. Availability for additional tests is unknown
			Large helium component test loops (for their status, see table 3)	Status see table 3
Qualification of air ingress calculation	Natural convection loop with internal graphite structures heated at high temperature and with possibility of air ingress		NACOK loop (Fig.16): Jülich (Germany), 1200°C (max.), 0,017 kg/s (air max.), 147 kW	Operational – Available

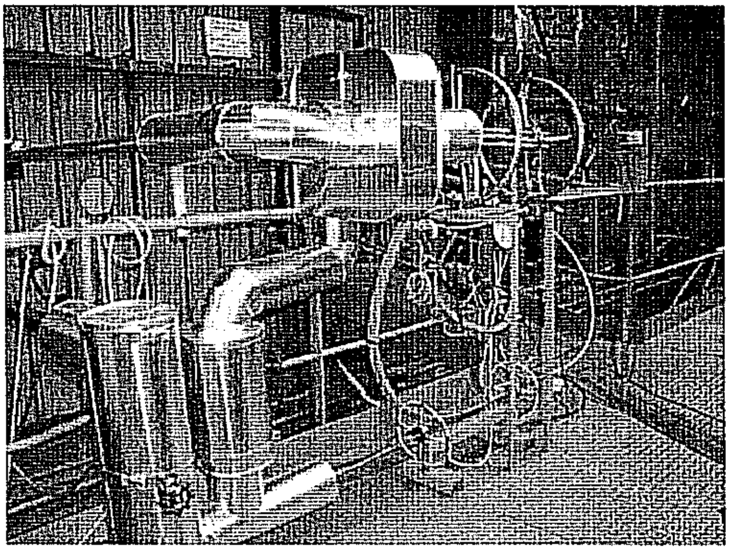
	Test need ##	**Test facility**	**Status #**
Qualification of fission product transport modeling	Tests with possible circulation, deposition and lift-off of aerosols simulating actual fission products		A dedicated facility to be defined

 # Status – Availability of test facilities that could be available for NGNP use is indicated. No formal agreement is implied. Generally such test facilities will require contractual agreements before usage is allowed.

Test need – Previously AREVA provide test needs during the pre-conceptual design studies performed in 2007. A comparison between test needs identified in this phase (conceptual design studies) tabulated here and those previously identified by AREVA are mutually inclusive.

Table 3: Large helium loops

	Turbo-machine testing loops			Component testing loops					
	EVO (turbine)	HHV (turbine)	CT-1383 (Main circulator)	KVK	CT-1312	HENDEL	HTF	HELITE	HELOKA
Location	Oberhausen (Germany)	Jülich (Germany)	OKBM (Russia)	AREVA (Germany)	OKBM (Russia)	JAEA (Japan)	Pelindaba (South Africa)	CEA Cadarache	FZK, Karlsruhe (Germany)
Power (MW)	120 (design value, operated only at 50)	100	n.a.	10	15	10	n.a.	1.2	3
Pressure (MPa)	3	5	4.9	4	5	4	9.5	8	8
Flow rate (kg/s)	80	200	95	3	6.5	4	2.5	0.4	1.8
T_{max} (°C)	750	850	345	950	965	1000	600	850-1000	500
Figures				Fig.17		Fig.18		Fig.19	Fig.20
Status/ Availability	Dismantled Complete set of data on EVO tests recovered by the European HTR program	Dismantled	Prolonged storage?	Dismantled	Prolonged storage?	Dismantled	Operational	Final design completed	In development Operational in 2009



Inlet gas temperature	# 200°C
Flow rate air N_2 He	# 150 g/sec # 100 g/sec # 70 g/sec
Heating power	# 4.5 kW
Pressure	0.2 MPa
Re	# 15 000

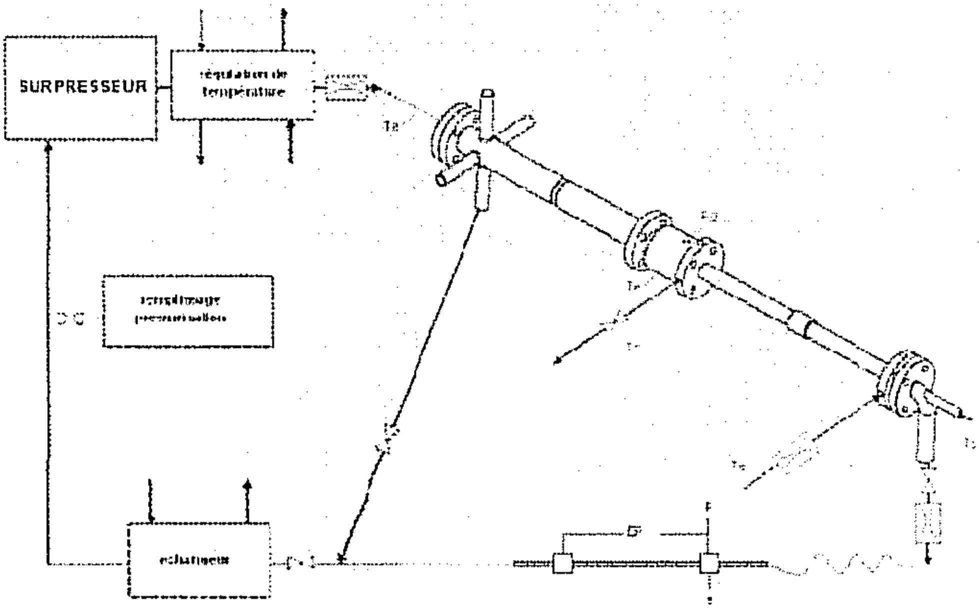


Figure 1: Gas heat transfer loop – Technical Center AREVA – Le Creusot

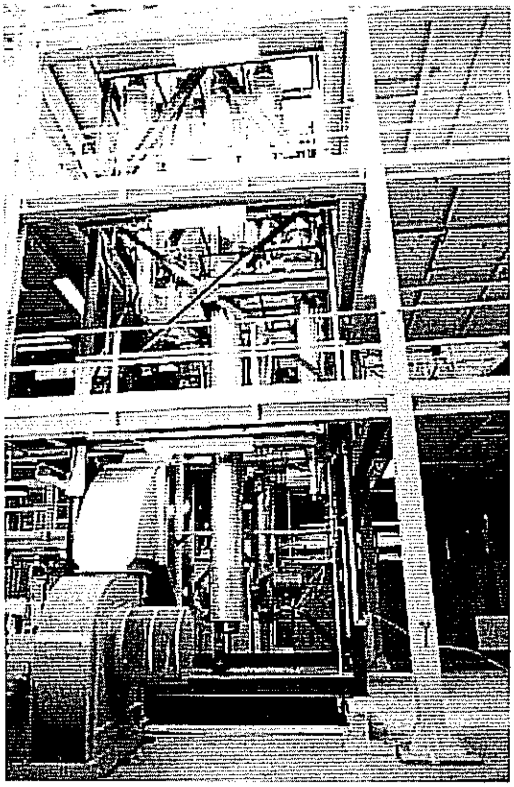
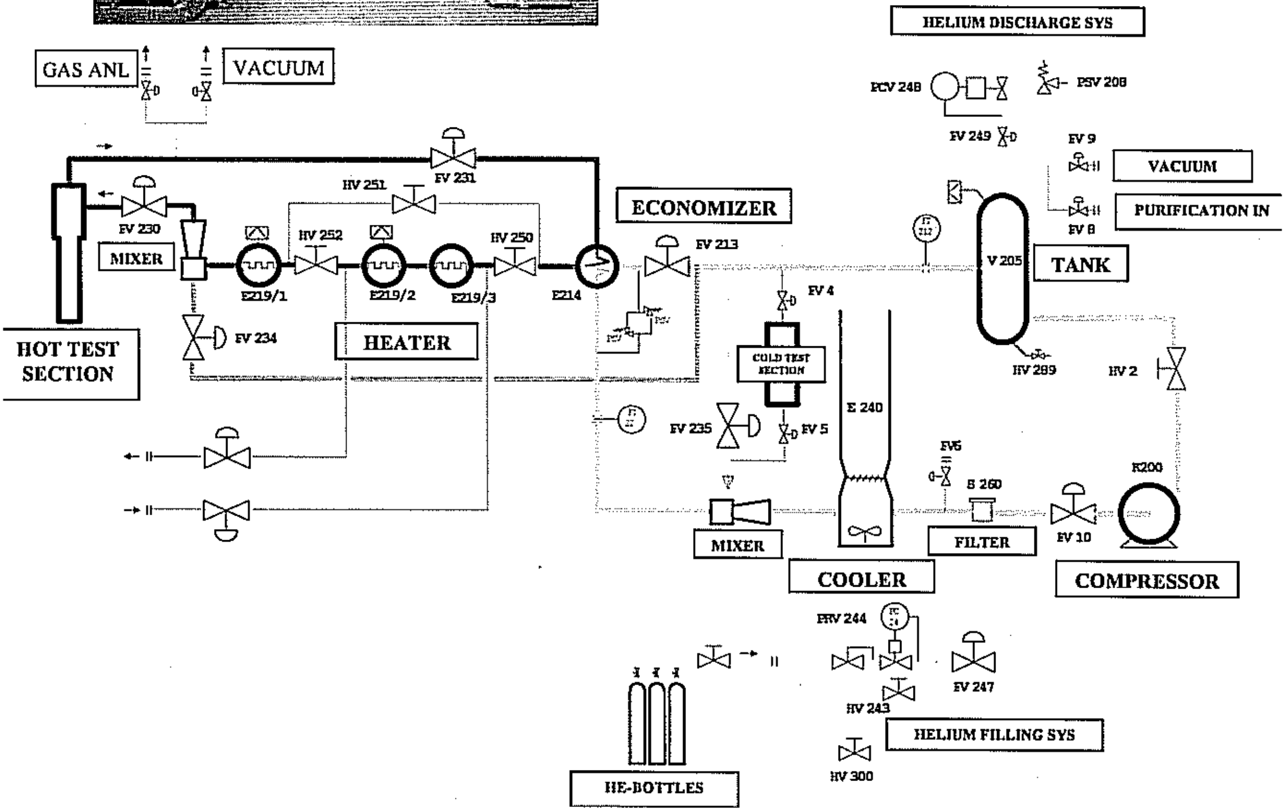


Figure 2: HE-FUS3 He loop
ENEA – Brasimone (Italy)

Cooling fluid	Helium
Mass flow rate (kg/s)	0.05 to 0.35
Maximum pressure (MPa)	10.5
Maximum temperature (°C)	510 °C
Compressor power (kW)	136
Heaters power (kW)	210



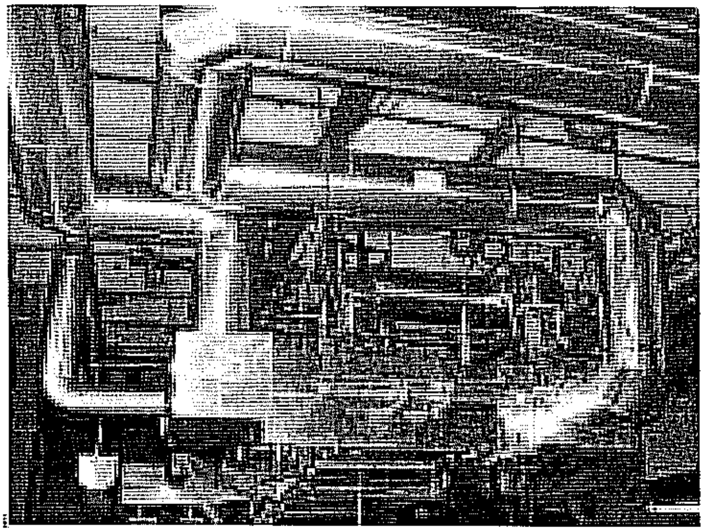
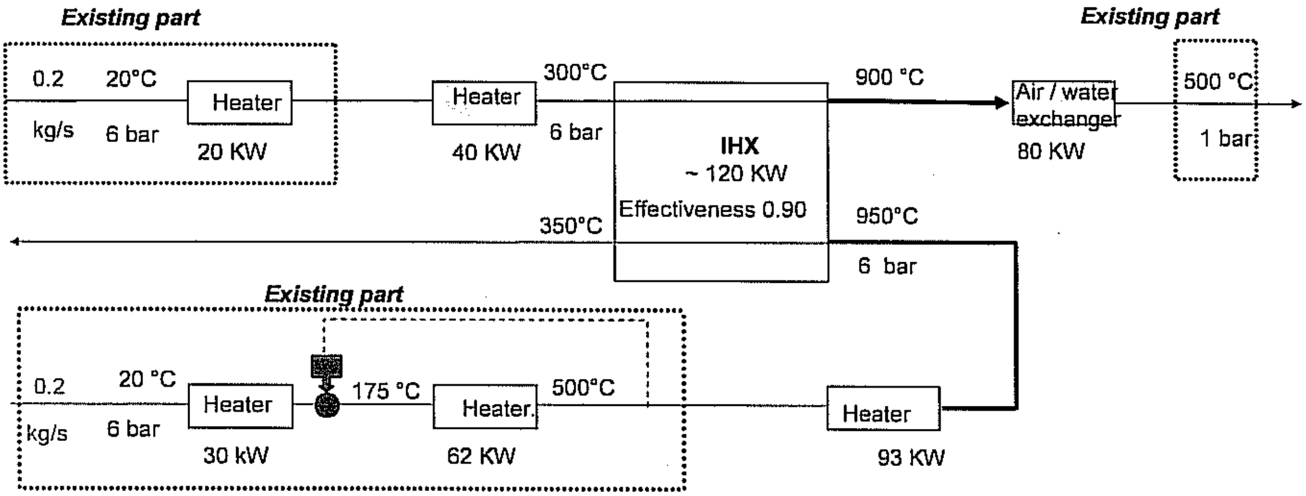


Figure 3: CLAIRE High temperature air loop CEA - Grenoble

Primary loop	
Cooling fluid	air
Mass flow rate (kg/s)	0.04 to 0.2
Pressure (MPa)	0.6
Temperature (°C)	510, upgrading planned to 950
Secondary loop	
Cooling fluid	air
Mass flow rate (kg/s)	0.04 to 0.2
Pressure (MPa)	0.6
Temperature (°C)	105°C (inlet)
Transferred power (kW)	~100
Thermal transients	Cool-down: ~ 300°C in 5s Heat-up: ~ 300°C in 120s



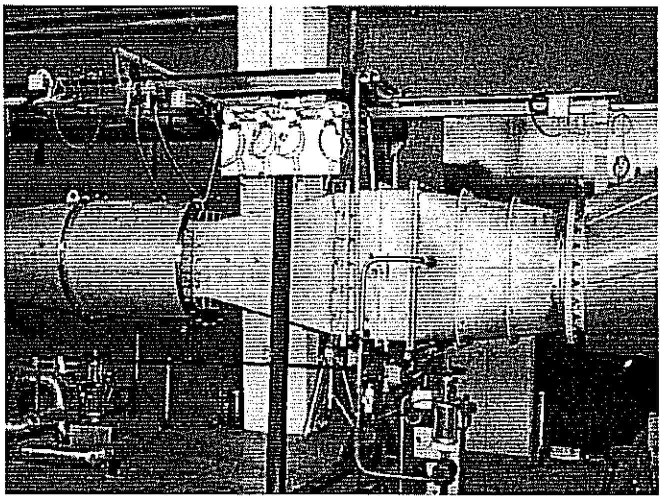
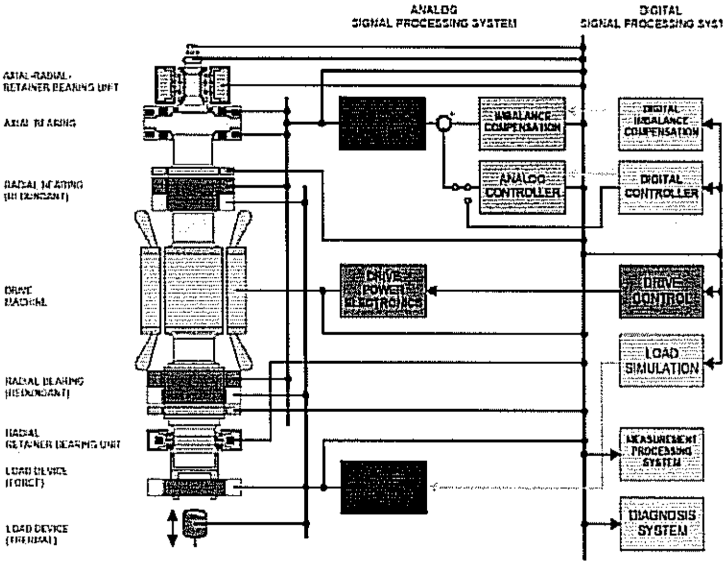


Figure 4: PAT large flow loop EdF Chatou

2 configurations

- **Air**
  - **Mass flow rate 1.3 kg/s**
  - **Max. pressure 1.5 Mpa**
- **Steam**
  - **Mass flow rate 5.5 kg/s**
  - **Max. pressure 2.3 Mpa**



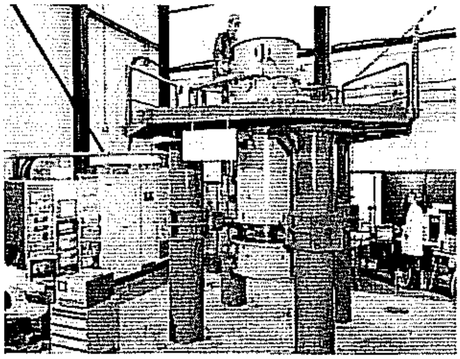
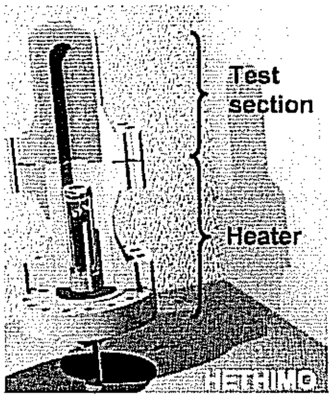


Figure 5: FLP-500, test bench for magnetic bearing supported rotor dynamics – IPM Zittau (Germany)



Tests conditions:

- **P = 10 MPa**
- **T = 1000 °C**
- **$\Delta P/\Delta t$ = 20 bar/s**

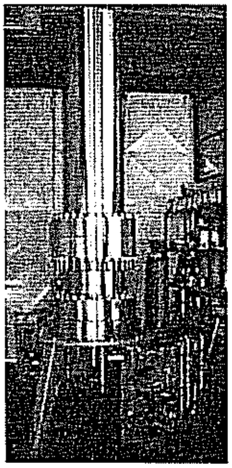


Figure 6: HETIMO test bench for hot duct thermal barrier performance – CEA Cadarache

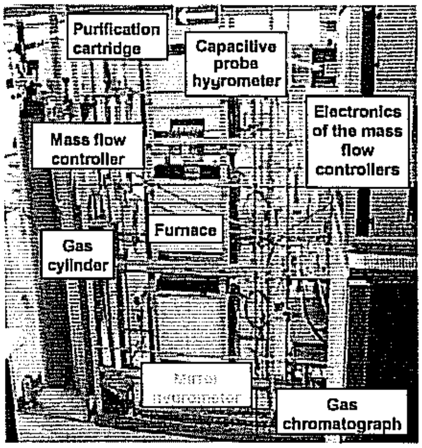
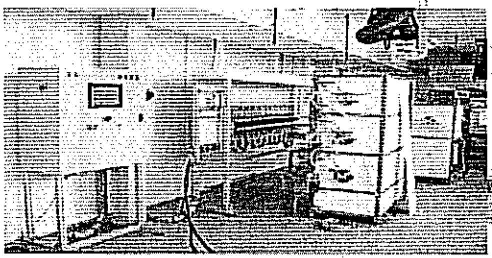
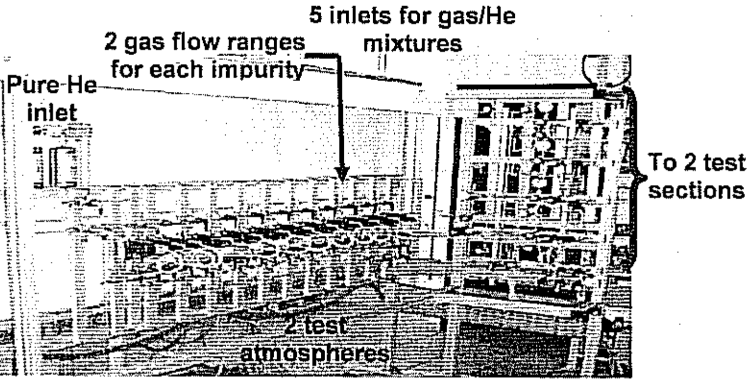


Figure 7: CORALLINE test loop, uniform corrosion in impure He atmosphere – CEA Saclay





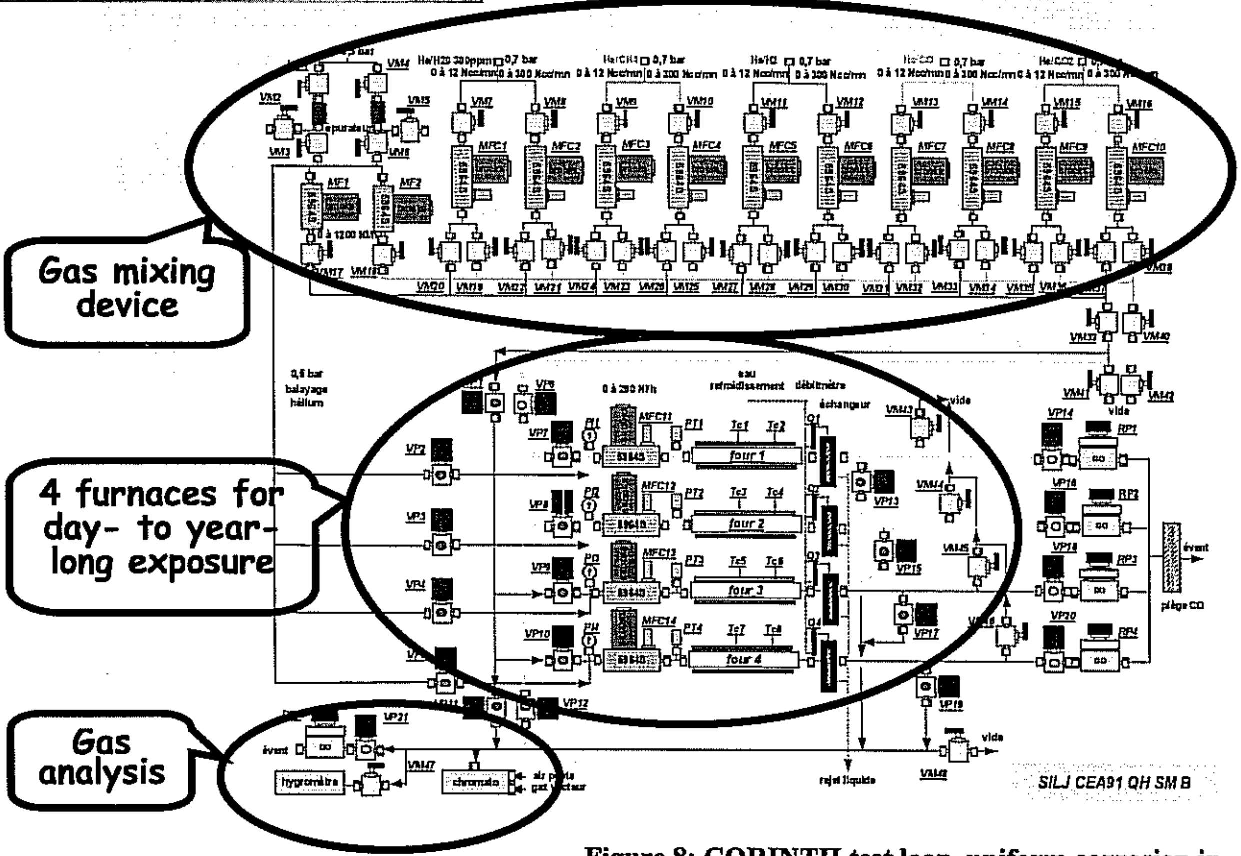


Figure 8: CORINTH test loop, uniform corrosion in impure He atmosphere – CEA Saclay

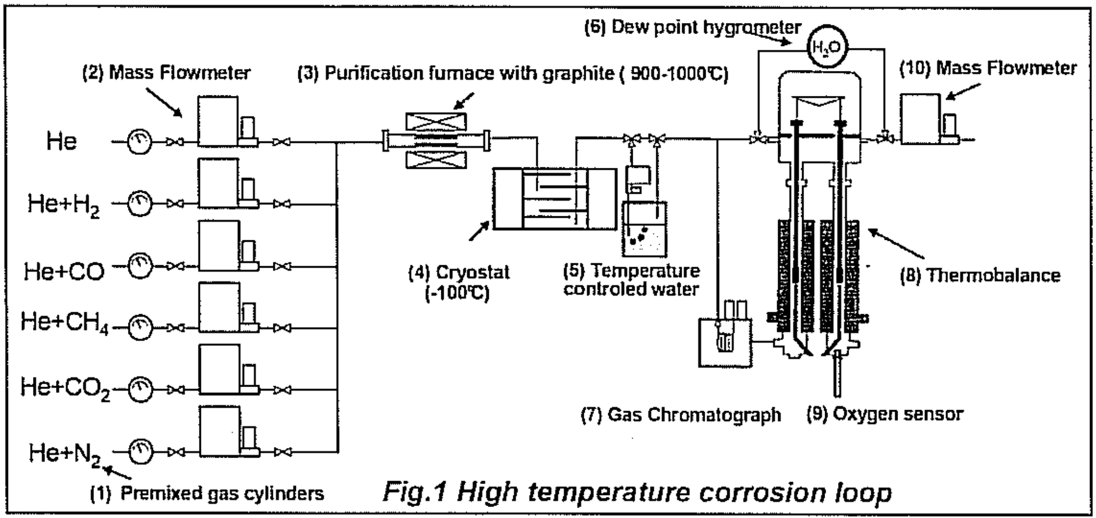


Fig.1 High temperature corrosion loop

- Wide range of concentrations (from the ppm to the %) (see 1 & 2) controlled by a gas chromatograph (7)
- Symetric thermobalance (8) for short tests or furnaces for long duration tests (up to 10000 hrs)
- Gas flow rate up to 36 Nl/h (10).
- Very low water level (cryogenic trap (4)) , adjustable (5) and controlled (6).

Figure 9: Uniform corrosion test loop in impure He atmosphere – AREVA NP, Le Creusot

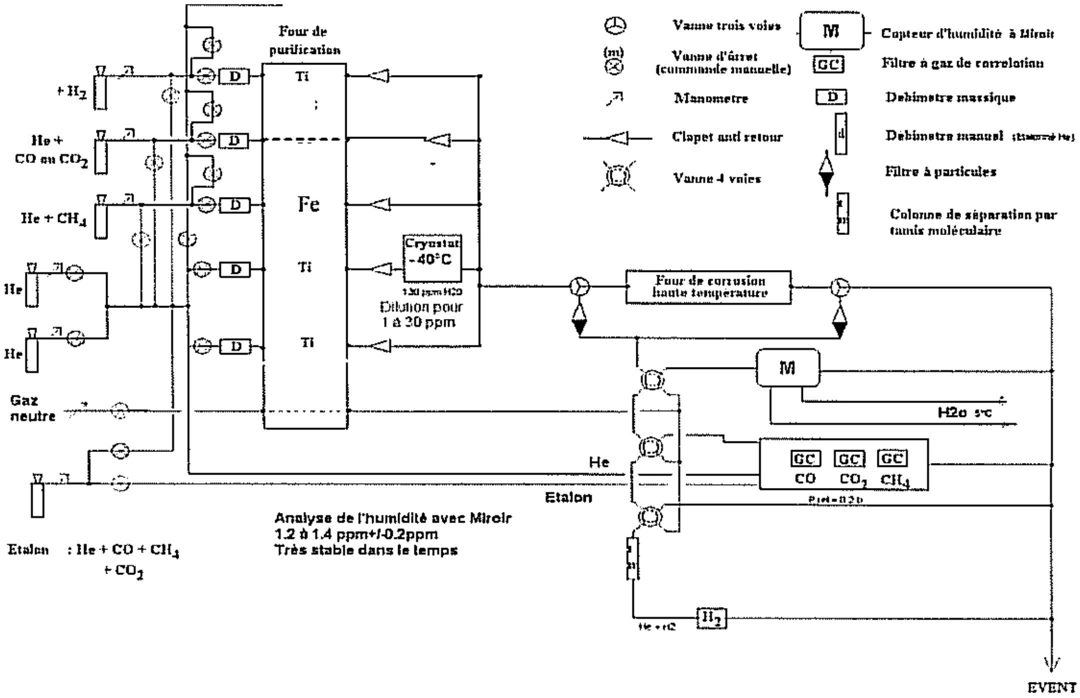


Figure 10: ESTEREL uniform corrosion test loop in impure in He atmosphere – EdF Les Renardières

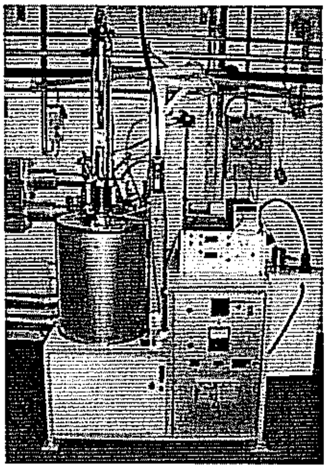


Figure 11: CORSAIRE creep test bench in impure He atmosphere – CEA Pierrelatte

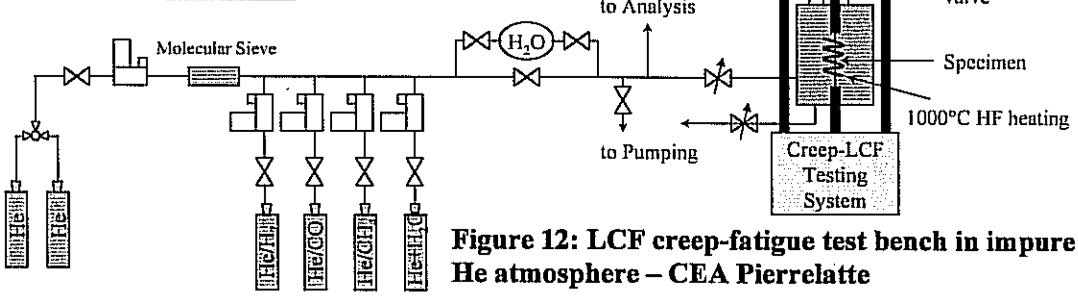
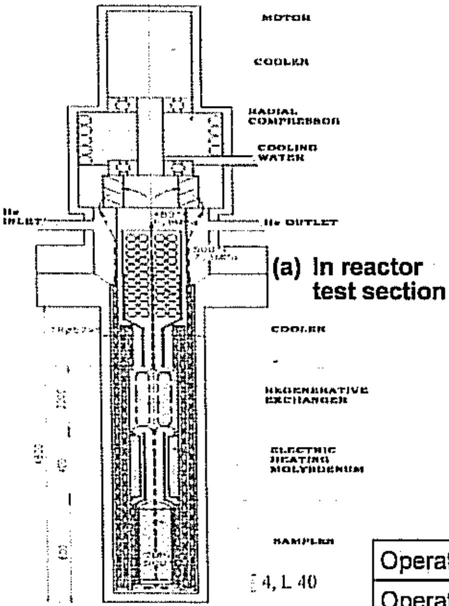
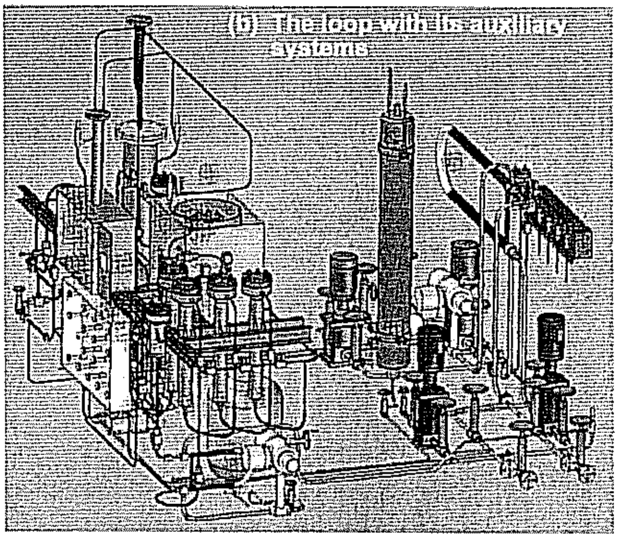


Figure 12: LCF creep-fatigue test bench in impure He atmosphere – CEA Pierrelatte



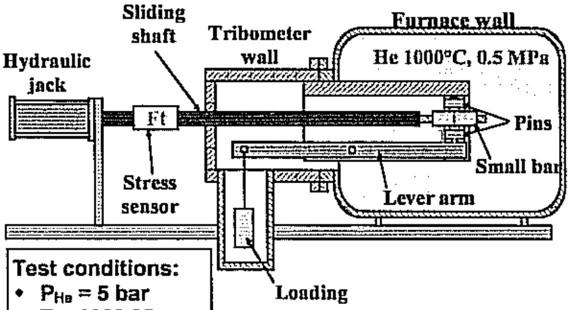
(a) In reactor test section

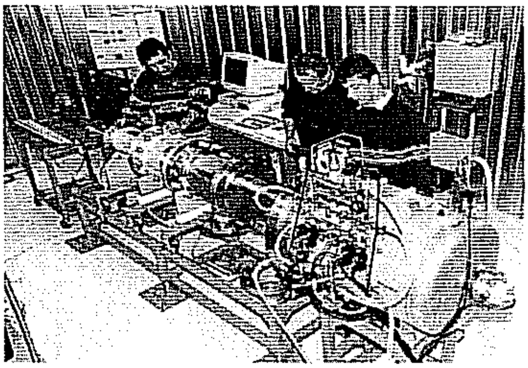


Operating medium	He
Operating pressure	7 MPa
Maximum pressure	8 MPa
Operating temperature	500-900°C
Maximum temperature	1000°C
Nominal flow	38 kg/hour

Impurity	Concentration $cm^3.m^{-3}$
H_2O, HTO, T_2O	1- 100
CO	10 – 500
N_2	10-500
H_2, T_2	10-500
CH_4	5-500
CO_2	1-500
O_2	1-100

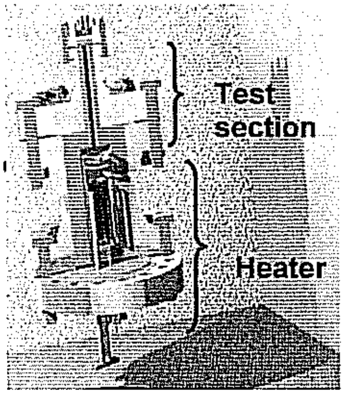
Figure 13: test loop for uniform corrosion under irradiation in impure in He atmosphere – UJV Rĕz (Czech Republic)





Test conditions:
- P_{He} = 5 bar
- T = 1000 °C
- Load : 0-20 MPa
- Sliding : 20 mm

Figure 14: He tribometer – CEA Cadarache



Tests conditions:
- P = 100 bar, T = 500 °C
- DN100

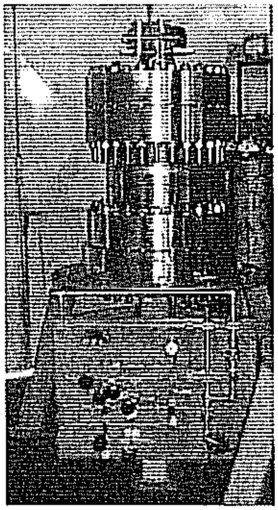
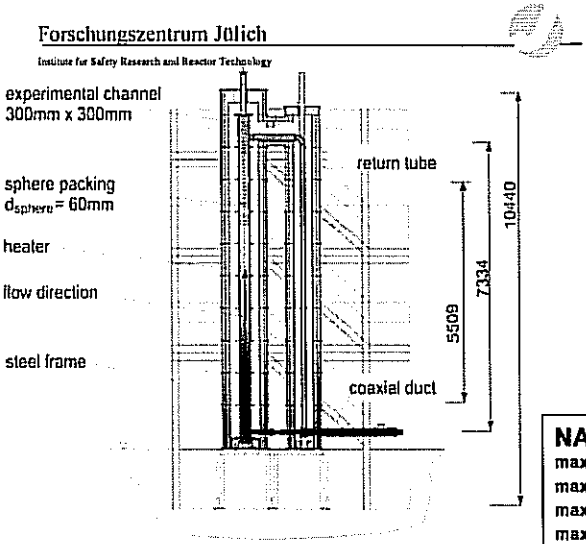
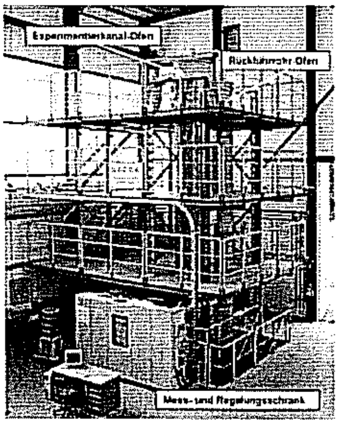


Figure 15: HETIQ test bench for seal leak tightness performance in He atmosphere – CEA Cadarache

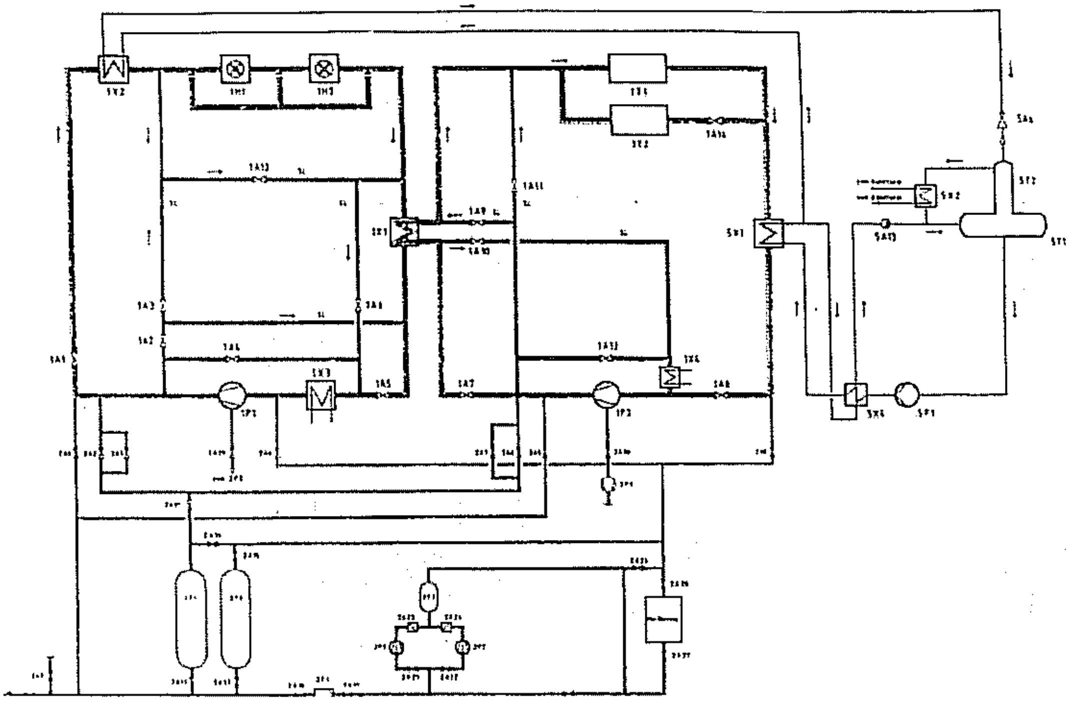




NACOK – Main Data:

maximal temperature in the experimental channel	1200 °C
maximal temperature in the return tube	800 °C
maximal air throughput	17g/s
max. number of temperature measuring points	82
max. number of gas analysis measuring points	26
number of gas velocity measuring points	2
maximal electric heating power	147 kW

Figure 16: NACOK air ingress integral loop – Jülich Research Center (Germany)



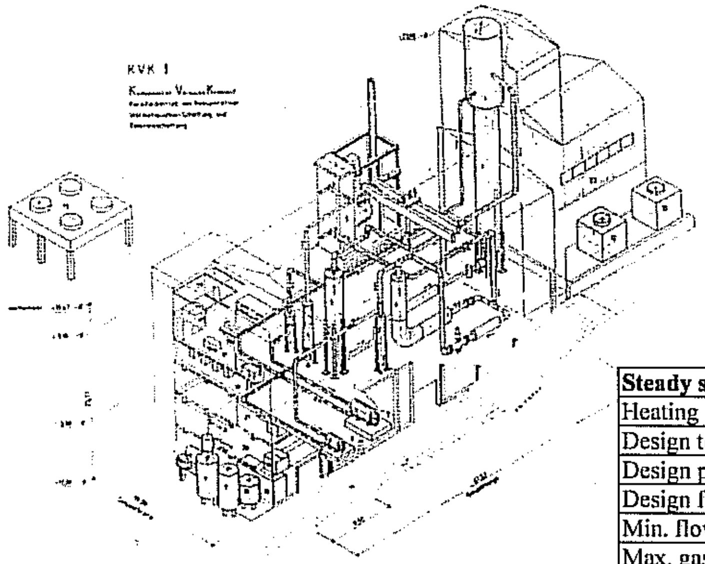
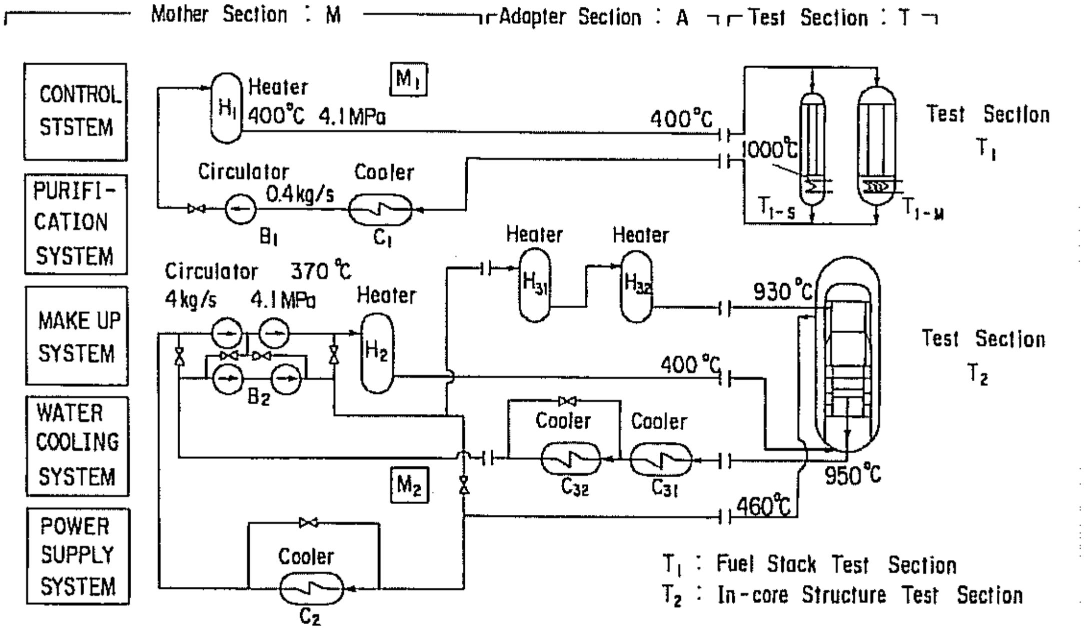


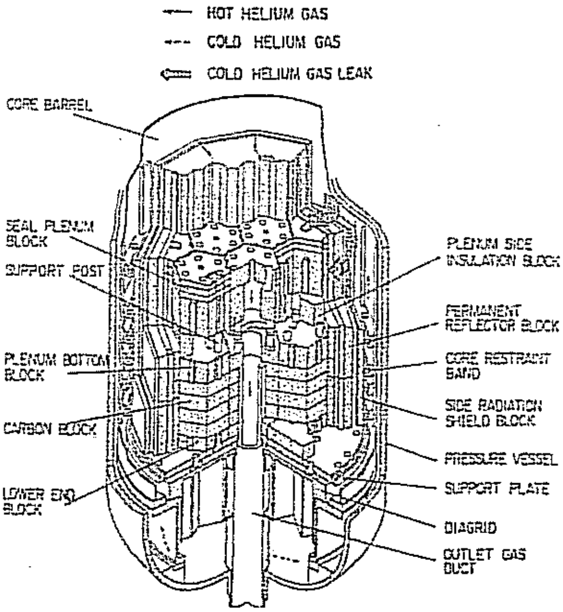
Figure 17: KVK He loop for component qualification, 10 MW – AREVA NP Karlstein (Germany)

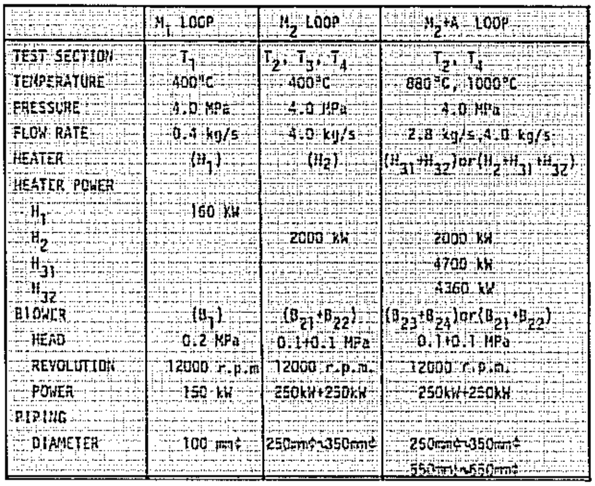
Steady state	
Heating power	10 MW
Design temperature	950°C
Design pressure	4 MPa
Design flow rate	3 kg/sec
Min. flow rate	0.6 kg/sec
Max. gas temperature	1000°C
Max. system pressure	4,6 MPa
Transients	
Temperature transient	≤200°C
Pressure transient normal max	0.3 MPa/sec 0.5 MPa/sec
Pressure difference primary/secondary	4 MPa
Pressure difference transient primary/secondary	0.5 MPa/sec
Overload test at 4 MPa, 950°C, with mass flow	3.2 kg/sec
Periodic transient	5°C/min, 950→650→950°C
Slow-down of mass flow	Within 1min to 0.21 kg/sec



(a) HENDEL flow sheet

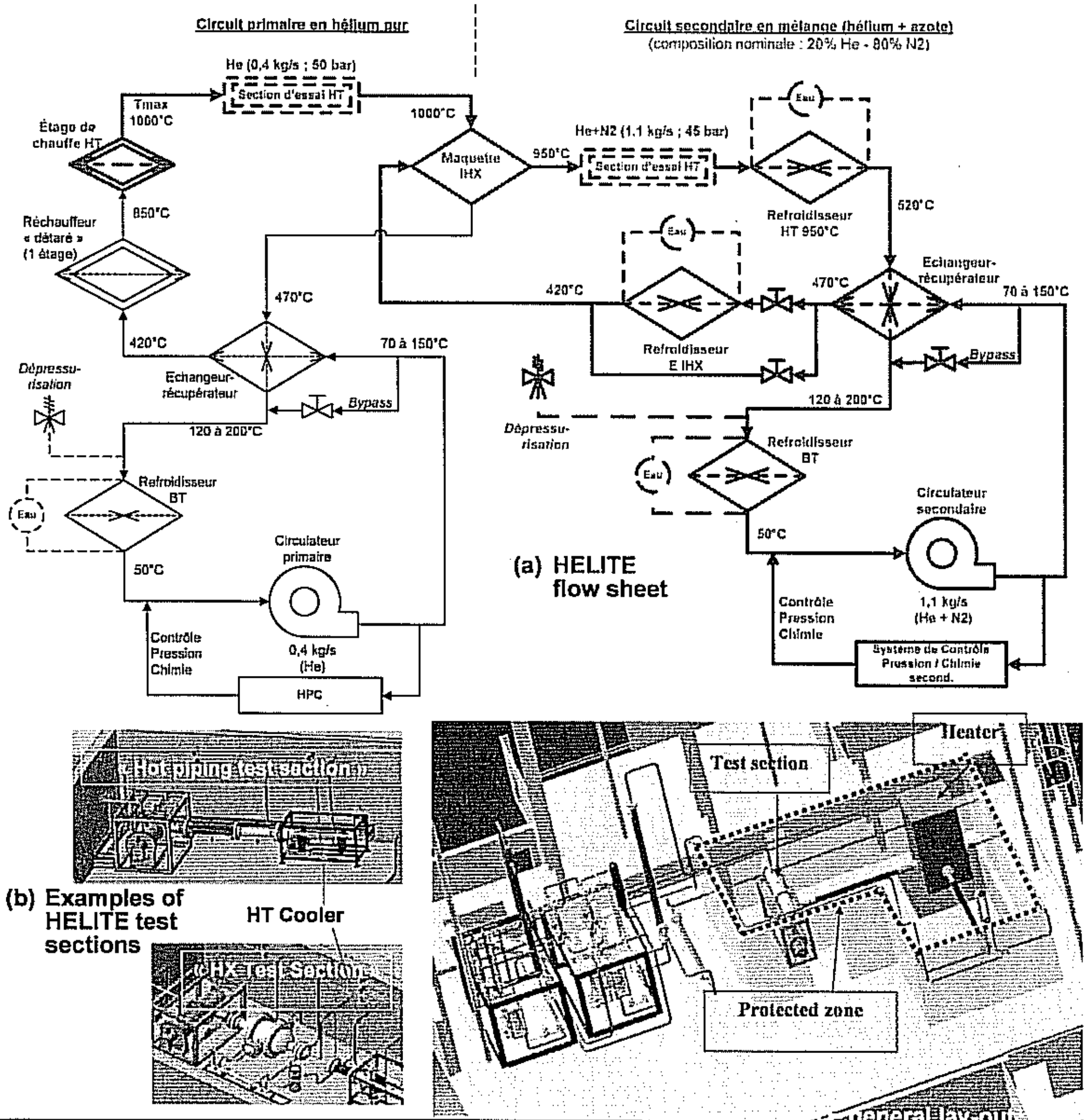
(b) T2 test section





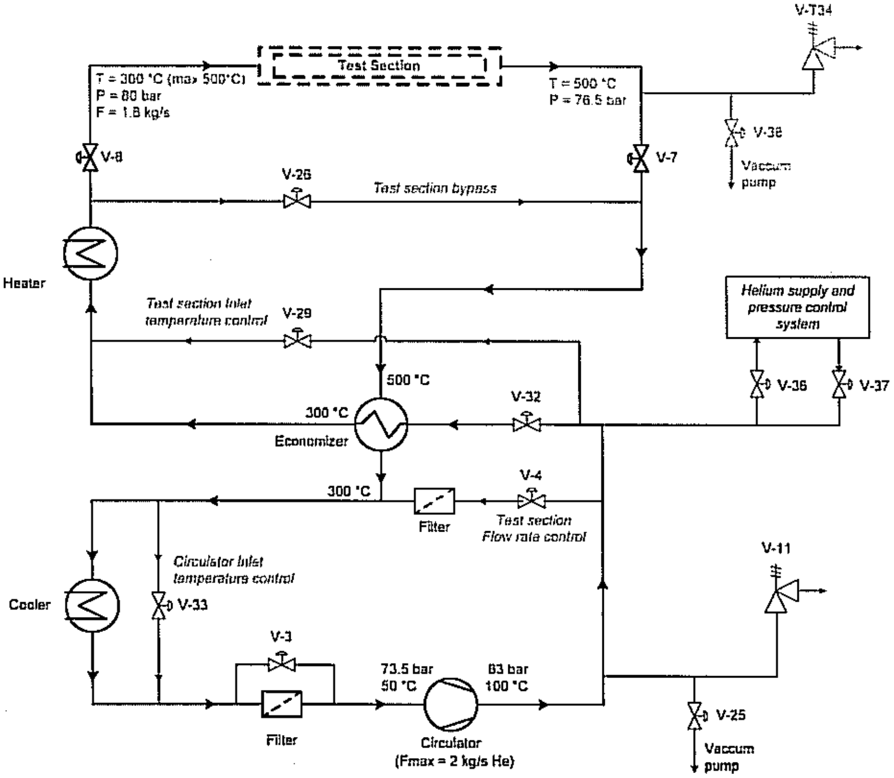
	M_1 LOOP	M_2 LOOP	M_2+A LOOP
TEST SECTION	T_1	T_2, T_3, T_4	T_2, T_4
TEMPERATURE	400°C	400°C	880°C, 1000°C
PRESSURE	4.0 MPa	4.0 MPa	4.0 MPa
FLOW RATE	0.4 kg/s	4.0 kg/s	2.8 kg/s, 4.0 kg/s
HEATER	(H_1)	(H_2)	(H_{31}+H_{32})or(H_2+H_{31}+H_{32})
HEATER POWER			
H_1	160 kW		
H_2		2000 kW	2000 kW
H_{31}			4700 kW
H_{32}			4360 kW
BLOWER	(B_1)	(B_{21}+B_{22})	(B_{23}+B_{24})or(B_{21}+B_{22})
HEAD	0.2 MPa	0.1+0.1 MPa	0.1+0.1 MPa
REVOLUTION	12000 r.p.m	12000 r.p.m.	12000 r.p.m.
POWER	150 kW	250kW+250kW	250kW+250kW
PIPING			
DIAMETER	100 mmϕ	250mmϕ~350mmϕ	250mmϕ~350mmϕ 550mmϕ~650mmϕ

Figure 18: HENDEL He loop for component qualification, 10 MW – JAEA Tokaimura (Japan)



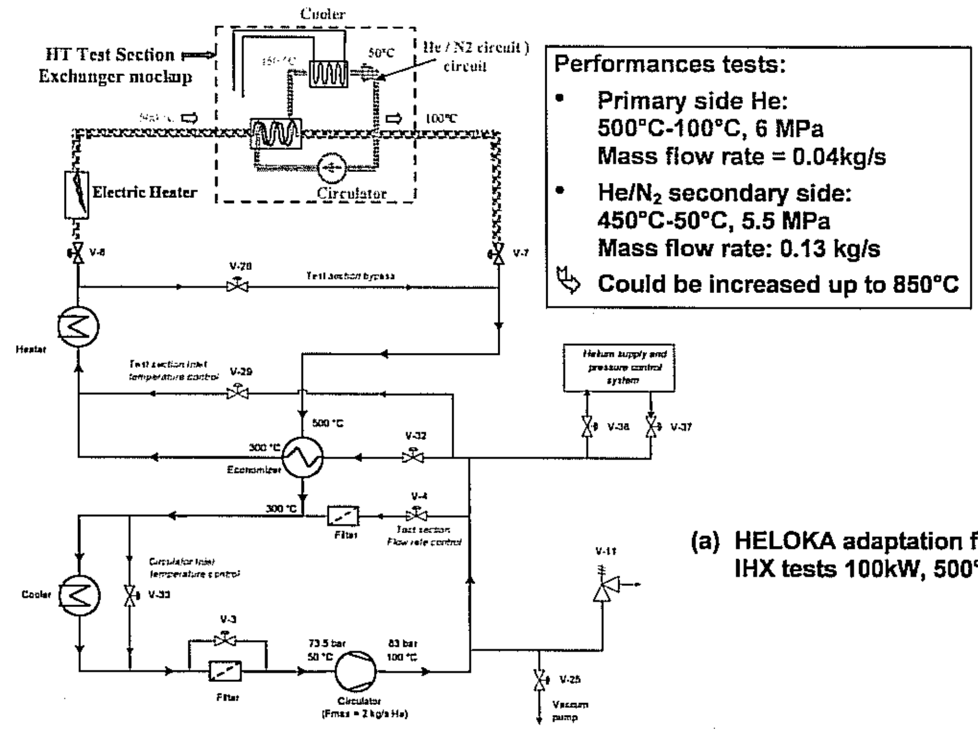
Primary loop	
Cooling fluid	He
Mass flow rate (kg/s)	0.4
Pressure (MPa)	4 to 8
Test section Temperature	500 and 950 °C (2 test sections)
Secondary loop	
Cooling fluid	He+N_2
Mass flow rate (kg/s)	1.1
Pressure (MPa)	4.5
Maximum temperature (°C)	900 °C
Transferred power (MW)	1
Bounding transients	Cool-down: 850 to 480°C in 100 s 5.5 to 2.5 MPa in 15 s Cycling

Figure 19: HELITE He loop for component testing, 1.2 MW – CEA Cadarache



	Nominal	Max
Helium flow rate (kg/s)	1.8	≈ 2, depending on circulator techno.
Test section Inlet temperature (°C)	300	500
Test section Outlet temperature (°C)	500	500
Pressure (Bar)	80	100 (loop design pressure)
Test section pressure loss (Bar)	-	3.5
Overall loop pressure loss (Bar)	-	9.5
Circulator compression factor	-	1.13
Cooler design removed power (helium / water heat exchanger) (MW)	2.3 (1,8 kg/s; 300 → 50°C)	4.4 (1,8 kg/s; 500 → 50°C)
Heater design power (electrical heater) (MW)	1.9 (1,8 kg/s; 100 → 300°C)	3.8 (1,8 kg/s; 100 → 500°C)

Figure 20: HELOKA He loop, 4 MW – Karlsruhe Research Center (Germany)

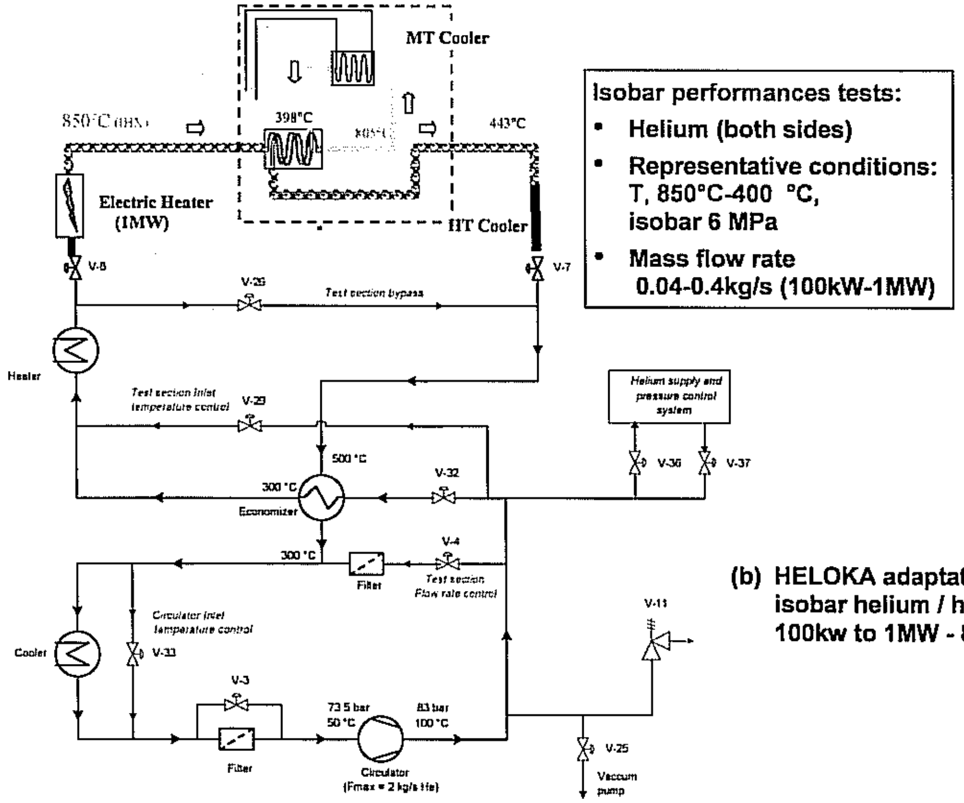


Performances tests:

- Primary side He:
  500°C-100°C, 6 MPa
  Mass flow rate = 0.04kg/s
- He/N_2 secondary side:
  450°C-50°C, 5.5 MPa
  Mass flow rate: 0.13 kg/s

↳ Could be increased up to 850°C

(a) HELOKA adaptation for IHX tests 100kW, 500°C

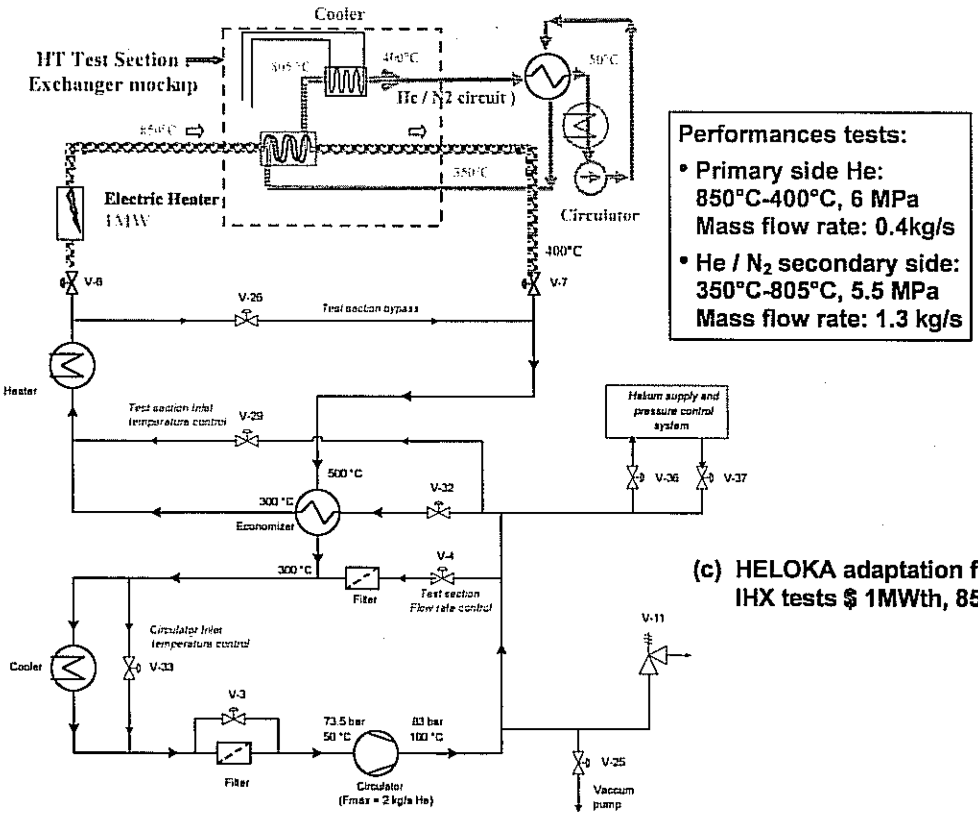


Isobar performances tests:

- Helium (both sides)
- Representative conditions:
  T, 850°C-400 °C,
  isobar 6 MPa
- Mass flow rate
  0.04-0.4kg/s (100kW-1MW)

(b) HELOKA adaptation for isobar helium / helium tests, 100kw to 1MW - 850°C

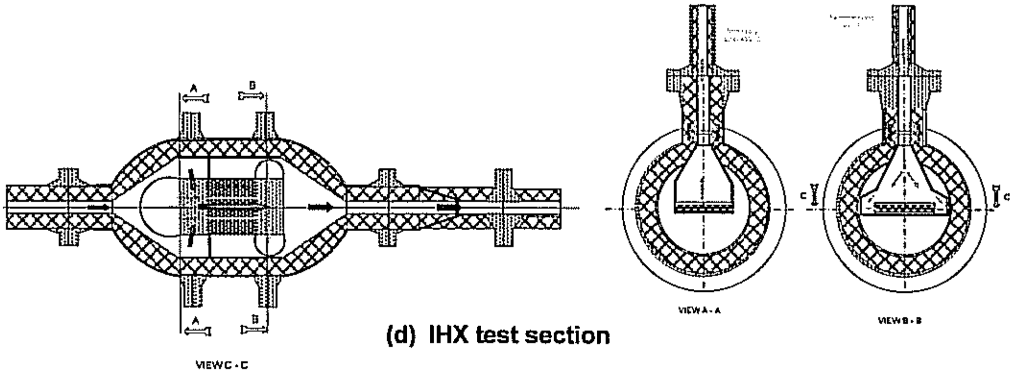
Figure 21: Possibilities of adaptation of HELOKA loop for adaptation to HTR test needs



Performances tests:

- **Primary side He: 850°C-400°C, 6 MPa Mass flow rate: 0.4kg/s**
- **He / N_2 secondary side: 350°C-805°C, 5.5 MPa Mass flow rate: 1.3 kg/s**

(c) HELOKA adaptation for for IHX tests $ 1MWth, 850°C



(d) IHX test section

Figure 21: Possibilities of adaptation of HELOKA loop for adaptation to HTR test needs (continued)

3. Functional and Operational Requirements

Within the framework of the NGNP Project, the most important use of the CTF is the qualification of the following NGNP indirect steam cycle concept reactor components:

- Tube and plate type IHX,
- Steam generator,
- Circulator,
- Hot gas ducts
- Hot valves
- Fuel and reflector graphite blocks

The facility must also provide test capability for major unique HTR plant systems including testing the performance of the Helium Purification System and provide capability for the injection of impurities.

Most of these tests are needed for later in the design process of the NGNP (i.e., occurring in the final design phase), with much of the earlier testing done within smaller, simpler loops (if available), or when the test involves the possibility of contamination, in a separate, dedicated facility.

To shorten the time required for the long-duration endurance testing necessary for qualification, secondary circuits of the loop would allow some tests to be done in parallel. Nevertheless, because of the difficulties cited earlier about the interaction of multiple circuits and the need for substantial testing requiring transients and cycling, only the functional requirements of two main loops—a primary loop and a secondary loop—are given here.

Because the availability of a dedicated loop for the NGNP Project earlier in the design process has clear benefits, which were discussed earlier, the requirements are specified in two phases. The first phase is a single loop, which would allow the facility to be available for tests that can be done using lower temperatures and a lower power level than the full-scale CTF and would allow the facility to be used for tests related to code qualification. This phase would also provide useful experience for the final development of the full-scale CTF. The second phase is a larger double loop, capable of being used for qualification of the reactor components.

3.1 Basis for NGNP CTF Requirements

The following helium loop test facilities are considered here:

- The HELITE test loop, a smaller test loop that was designed mainly to address the needs of plate IHX preliminary tests and HPS qualification. The design of this loop was performed by AREVA and is finalized.
- The KVK loop, a large-scale loop that operated in the German Technical Center of AREVA NP (formerly INTERATOM) from 1982 until 1990 which was designed to

address the needs of an indirect steam cycle concept. Note that the KVK documentation is available in AREVA.

- The HENDEL loop, a large-scale loop that operated in Japan from 1982 to 1995. This loop was designed to address the needs of HTTR. Major equipment for this loop was provided by MHI.

The experience gained in the design and operations of these test loops is the basis for AREVA recommendation to address the main needs of the NGNP Project except for the direct cycle needs.

The following sections provide an over view of the functional and operational requirements of these loops which are then used to derive the functional and operational requirements for the CFT by analyzing the mission needs of the NGNP.

3.2 The HELITE Test Loop

The HELITE test facility was designed as a two-loop test facility, which is planned to be built in two phases:

- Phase 1: A single helium loop capable of 850 °C
- Phase 2: A primary helium loop capable of 1000 °C and a secondary helium/nitrogen loop

The functional requirements for Phase 1 are given below:

- Loops: one primary loop consisting to two test sections
    - A high temperature section capable of temperatures up to 850°C
    - A mid-temperature section capable of temperatures up to 500°C
- Gas: helium
- Flow rate: 0.1-0.4 kg/s
- Thermal power: 1 MW
- Pressure: 40-80 bar
- Temperature transients: ± 100 °C/min for 5.5 minutes

For Phase 2, an additional heating module is added to the primary loop and a second loop is constructed. The functional requirements for Phase 2 are listed below:

- Primary loop:
    - consists of two test sections
        - A high-temperature section capable of temperatures up to 1000 °C
        - A medium-temperature section capable of temperature up to 500 °C
    - Gas: helium
    - Flow rate: 0.1–0.4 kg/s
    - Thermal power: 1.2 MW

  - Pressure: 40-80 bar
  - Temperature transients: ±100 °C/min for 5.5 minutes
- Secondary loop:
  - Gas: helium/nitrogen mix
  - Flow rate: 1.1 kg/s
  - Pressure: 45 bar

3.3 The KVK Test Loop

The KVK test facility was a larger test facility, which was built in Germany for the HTR-Module program. During its first two years of operation, it had only one loop. Beginning in 1984, however, it was converted to a two-loop facility and was operated as such until 1988, when it returned to single-loop operation. During its double-loop phase, up to 7 test objects could be in operation under reactor conditions simultaneously.

From the design and operation data that are available, the equivalent functional and operation requirements for the KVK facility can be summarized as

- Loops: Initially one, second loop added later
- Temperature: up to 950 °C primary / 900 °C secondary
- Gas: helium
- Flow rate: 3 kg/s (max 4.6 kg/s)
- Thermal power: 10 MWt
- Pressure: 40 bar
- Temperature transients: ±200 °C/min
- Pressure transients: 5 bar/s

KVK loop was dimensioned by the size of the IHX mock up. It was necessary to test at least three full rows of tubes (cylindrical tube assemblies) to completely represent the thermal-hydraulic behavior of the full-scale IHX unit. Since past HTR nuclear projects considered 125 MWt IHX units with a primary flow rate of 35.6 kg/s, testing three rows of tubes of the mock-up leads to a 10 MWt mock-up with 117 tubes and a primary flow rate of 3 kg/s.

3.4 The HENDEL Test Loop

The HENDEL (Helium Engineering Demonstration Loop) was a test facility meant at performing full-scale demonstration tests on the core internals and high temperature components for HTTR (High Temperature engineering Test Reactor). The test loops of HENDEL consist of Mother (M), Adaptor (A) and Test (T) sections (Figure 18). The Mother and Adaptor (M+A) section can supply helium gas with a maximum flow rate of 4 kg/sec, a maximum pressure of 4 MPa and a maximum temperature of 1000 °C to the test section. The test section has two sub-sections, called T_1 and T_2, to investigate heat transfer and flow characteristics of the fuel block and thermal-hydraulic characteristics and structural integrity of the core support structures of the HTTR.

The M+A section completed in March 1982 has been operated for more than 22,900 hours till August 1995. The T_1 and T_2 sections completed in March 1983 and June 1986 have been operated for more than 19,400 hours and 16,600 hours, respectively. In this period, a large number of tests have been conducted to verify the component performance and safety feature of the HTTR system, and the valuable operating experience of the HENDEL for more than ten years was accumulated. The design and operational data of HENDEL can be summarized as follows,

- M_1 loop: the M_1 loop supplies T_1 test section with helium gas flow.
    - Maximum Flow rate: 0.4 kg/s
    - Heater power: 0.16MW
    - Pressure: 4 MPa
    - Maximum Temperature: 400 °C
- M_2 +A loop: the M_2 +A loop supplies T_2 test section with helium gas flow.
    - Maximum Flow rate: 4 kg/s
    - Heater power: 10MW
    - Pressure: 4 MPa
    - Maximum Temperature: 1000 °C
- T_1 test section: fuel stack test section
    - Main Objectives of testing: to investigate heat transfer and fluid dynamics performance of HTTR fuel elements (heat transfer in normal conditions and with channel blockage, hydraulic tests and in particular cross flow tests) and reliability of control rod mechanisms.
    - Helium gas is supplied from M_1 loop and enters from upper nozzle and flows downward the test assembly. The temperature of helium gas at outlet of tested fuel columns reaches 1000 °C and is directly cooled to 400 °C by inter-cooler and returns to M_1 loop. The temperature, pressure, velocity, vibration and flow rate are measured to evaluate HTTR fuel heat transfer and fluid dynamics.
- T_2 test section: in-core structure test section
    - Main Objectives of testing: to verify high temperature performance of HTTR core bottom structure and to confirm the structural integrity of thermocouples installed at core bottom
    - T_2 test section connecting with M_2 +A loop is capable of testing the core bottom plenum structure of 7 regions. The performance on integrity of structure, gas seal, thermal insulation and gas mixing in the HTTR was tested.

- The thermal insulation performance of a single pipe and coaxial double pipe hot gas duct was also tested

3.5 NGNP Component Test Facility F&OR

The design proposed by AREVA for the NGNP is an indirect steam cycle configuration (see Fig. 22 for a layout example) with two (or three) main primary loops. In this configuration there are two 300 MWt IHX units, two 8 MW circulators and one auxiliary primary loop with a 60 MWt plate IHX and a small circulator.

A primary flow rate of approximately 150 kg/s is required for two 300 MWth ***IHX*** units. Therefore, it is necessary to test a minimum of 3 rows, but with a larger number of tubes per rows than for past German designs. Based on the higher primary/secondary flow rates and the dimensional changes needed to maintain the same fluid velocities in the hot header and in the secondary pipes, the diameter of the hot header must be increased by a factor of roughly $(150/35.6)^{1/2} \approx 2$.

The NGNP IHX mock up therefore has around 2 x 117 = 234 tubes and the primary flow rate is approximately 10 kg/s, since the total number of tubes for the NGNP IHX units is around 3000 with a primary mass flow rate of 150 kg/s.

As in KVK, this flow rate value defined for the IHX should also cover testing needs for a ***steam generator***.

For the ***circulator*** a scale factor of 1/3-1/5 is considered to be the limiting size of a representative machine from a thermal-hydraulic point of view. This leads to a machine operating with a flow rate between 6 and 16 kg/s for the NGNP. Larger circulators can be tested for short period of time by supplementing the flow in the loop with helium discharged from a tank. This kind of discharge test is also proposed for full-scale hot valves.

For tests of the ***hot gas duct***, the flow inside the loop needs to be representative of the conditions in the NGNP only near the inner thermal insulation. Therefore, it is possible to use a test section with the exact diameter of the ducts by using a plug to block the central part of the pipe, which reduces the area of the flow to a much smaller annular space. Current reference designs for the NGNP specify an inner diameter of approximately 1.8 m for the hot duct. Thus, a flow rate of 150 kg/s is equivalent to a flow rate of 30 kg/s in a 10 cm wide annular space between the pipe and a central plug. By only testing part of the pipe, the necessary flow rate can be even further reduced. For example, a 90° section of the component would require a flow rate of only 7.5 kg/s through the space between the plug and the pipe.

A flow rate of approximately 3 kg/s is anticipated for the *fuel block* tests.

For the ***core inlet and outlet plenums***, thermal-hydraulic helium tests would require very large flow rates to be representative of even a modest subsection of the reactor. For example, a sector of 30° leads to a flow rate of 25 kg/s. Such tests can be performed using air, however and this is the recommended approach.

For ***helium turbo machinery*** a scale factor of 1/3-1/5 leads to a flow rate of 12-33 kg/s.

Therefore, the considerations above suggest that the main NGNP needs can be addressed by a CTF loop with a 10 kg/s mass flow rate except for the helium turbo-machine tests of the direct cycle option and the core inlet and outlet plenums which can be tested in air.

For ***materials*** qualification, Helium Purification System qualification and plate IHX preliminary testing the HELITE configuration and requirements are recommended.

For pressure and thermal transient test requirements the KVK figures are useful guides for indirect steam cycle needs.

AREVA recommends two test facilities; each of which will be designed, constructed, and operated separately. The first facility is a 1 MWth test facility based on the HELITE configuration, which will be used for materials qualification, Helium Purification System qualification, plate IHX preliminary testing, qualification of CTF components and getting a first feedback from experience of helium circuit operation. The second facility is a larger 25-30 MWth test facility that is based on experience acquired in designing and operating the KVK and HENDEL test facilities. This large facility will be designed, built and operated in two phases and it will be suitable and available for the follow-on design progression of NGNP and commercial HTR component qualification, pressure transients, and thermal-fluidic transients.

The functional and operation requirements of the larger facility can be summarized as follows:

Phase 1: Single loop

- Temperature: up to 850 °C

  Justification - This temperature is sufficient for code qualification purposes, early testing of materials and components, particularly components that are not normally exposed to the very high temperatures in the reactor.

- Gas: helium
- Flow rate: 10 kg/s
- Thermal power: ~ 25 MW

  Justification - The flow rate and power level are chosen to accommodate mock-ups, which either are reduced in scale or are full-scale mock-ups of the component with only part of the component represented (e.g., a tubular heat exchanger with a reduced number of tubes or a single module of a multi-module component). Where a larger helium flow rate is required, the loop's flow rate can be augmented by such techniques as discharge from a pressurized helium tank or by introducing a cylindrical plug in the middle of the channel, as discussed earlier.

- Pressure: 40-70 bar

  Justification - The pressure range is chosen to encompass the expected design pressure inside the vessel of the NGNP, while accommodating certain tests that will be performed at higher pressures.

- Temperature Transients: ± 200 °C/min

Justification - It is envisioned that a wide variety of transient tests and endurance testing involving cycling will be performed. The bounding cases involve thermal shock testing that will be needed for qualification of some of the components, e.g., the IHX. The rate of change given here provides for a change in temperature from 1000 °C to 300 °C in 3.5 minutes.

Phase 2: Two loops

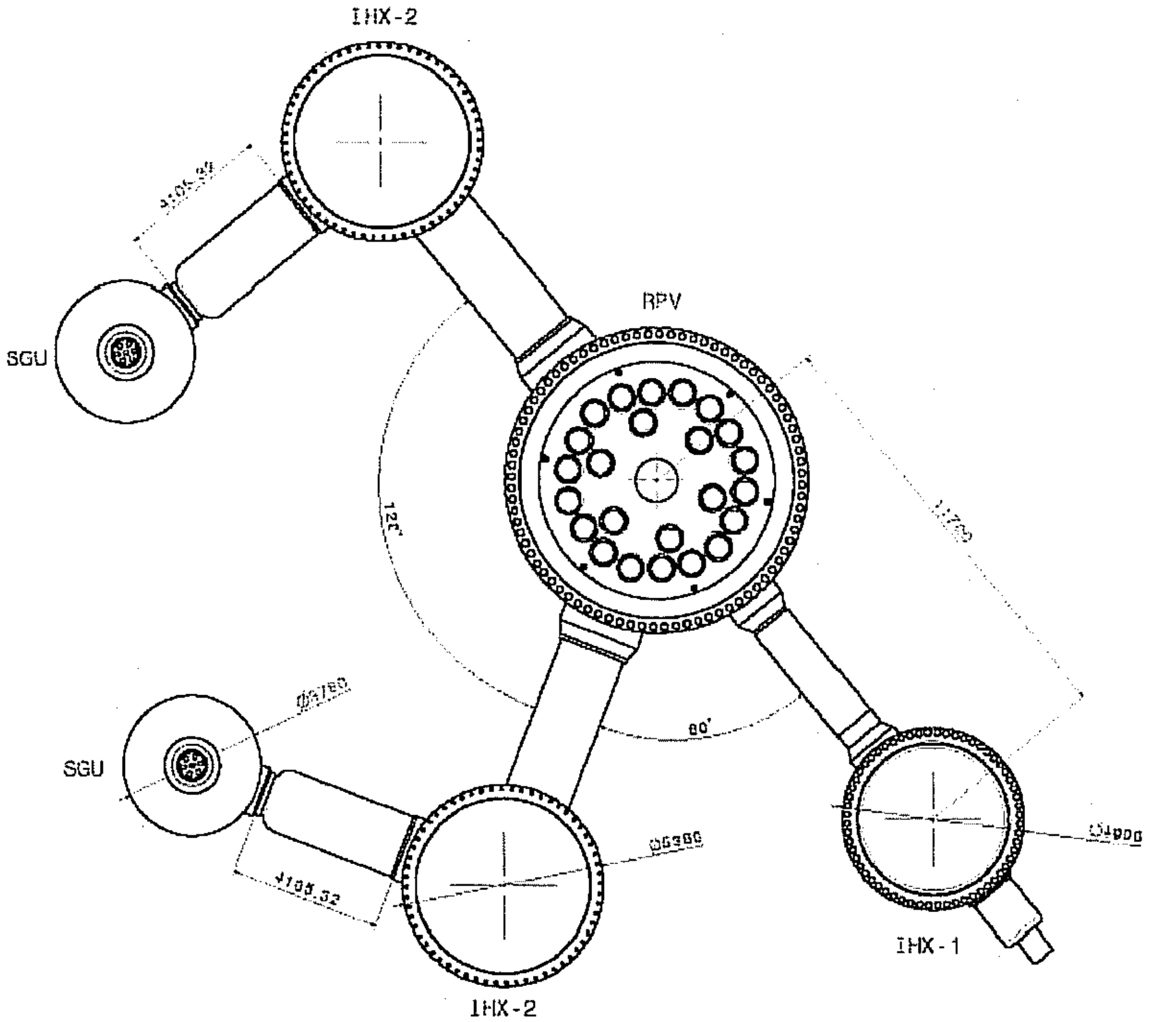
The power level of the heating unit for primary loop is increased and higher temperatures are supported. Other requirements remain the same as in Phase 1.

- Primary loop:
    - Temperature: up to 1000 °C
    - Gas: helium
    - Flow rate: 10 kg/s
    - Thermal power: 30 MW

      Justification - These changes are sufficient to achieve the higher temperatures necessary for tests and qualification of components for the NGNP, which could have a power output as high as 600 MWth and outlet temperatures as high as 950 °C.
    - Pressure: 40–70 bar
    - Temperature Transients: ±200 °C/min
- Secondary loop:

  A secondary loop is added for additional tests and capabilities, such as testing of helium-helium heat exchanger, heat exchangers with other gases in the secondary circuit or even steam exchangers. Therefore a water-steam secondary system must be foreseen or at least provisions for being able to add it later. The functional and operational requirements for the secondary loops are summarized below:
    - Temperature: up to 950 °C
    - Gas: helium or other gas, mixture of gas or steam
    - Flow rate: 10 kg/s
    - *Justification* - The temperature and flow rate accommodate heat transfer from the primary to the secondary loop in the qualification of IHX components. These requirements should be sufficient to support development and testing of process heat applications in conjunction with the NGNP Program.
    - Pressure: 35-75 bar
    - *Justification* - This pressure range is sufficient to support test conditions for the IHX and allows testing of the full range of situations when the pressure of the secondary side is higher or lower than the pressure on the primary side.

Figure 22: NGNP Indirect Steam Cycle Configuration



TOP VIEW
Scale: 1:80