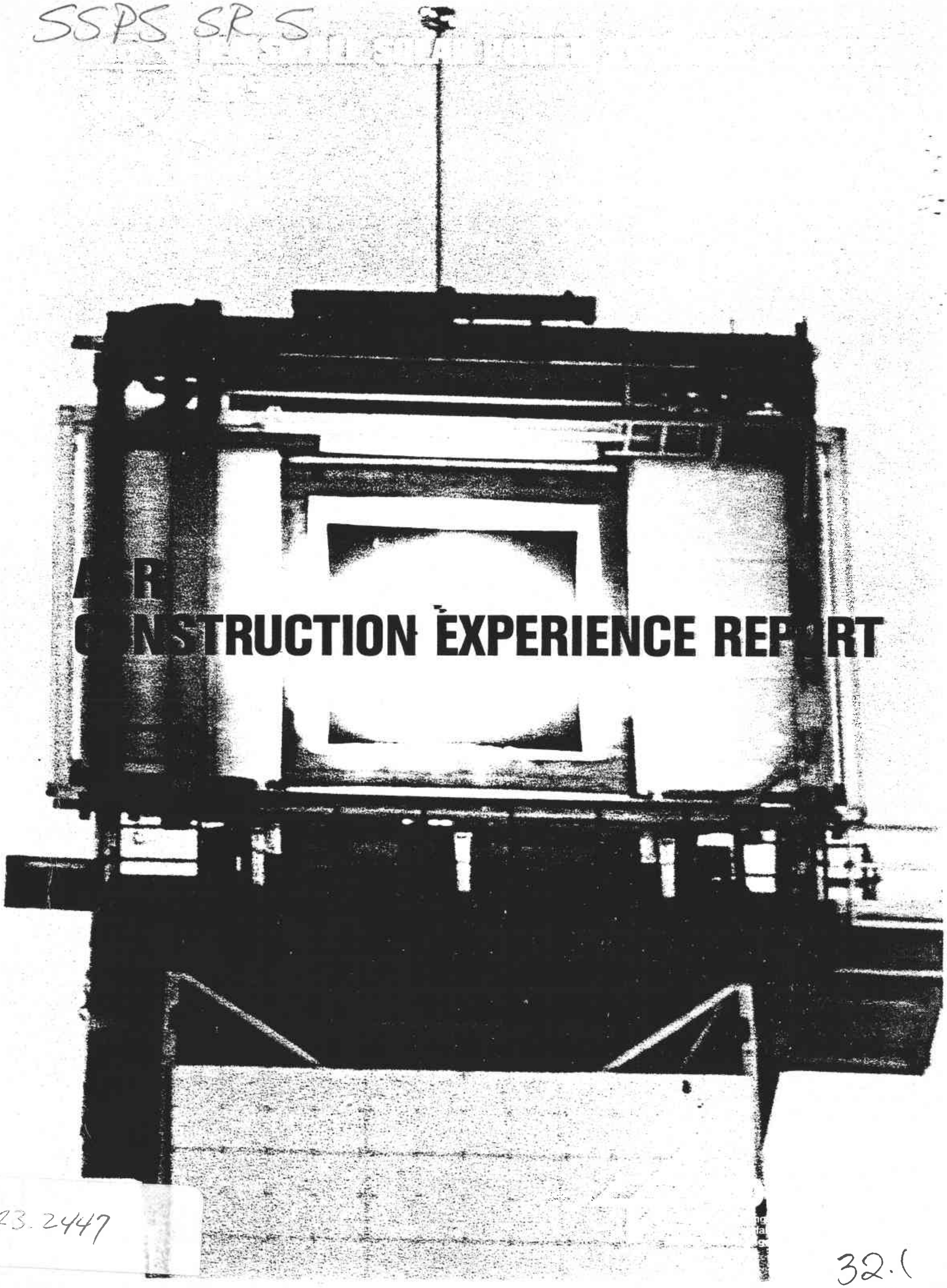
SSPS SR 5



A R
CONSTRUCTION EXPERIENCE REPORT

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SSPS SR 5

SSPS-CRS Advanced Sodium Receiver

Construction Experience Report

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FOREWORD

When the Central Receiver System of the SSPS Project started operation in September 1981, it was the first solar tower plant throughout the world to apply liquid sodium as a coolant. It was therefore only understandable that construction of its Receiver for the concentrated solar radiation was designed in a somewhat conventional manner. Good experience and undisturbed operation, however,justified very soon a more advanced receiver design in order to make full use of the good thermo-dynamic properties of sodium.

This report documents in a short form the experiences from design, manufacturing, assembling and acceptance testing of a second and more advanced receiver, the so-called SSPS-ASR (Advanced Sodium Receiver). At the time of the publishing of this report, the ASR has fully proved its design expectations. With its approximately 90% efficiency it became one of the best, if not the best solar receiver presently existing.

The realization of this challenging project was carried out with excellent cooperation between the Italian companies involved and their representatives, the customer, DFVLR, and the SSPS Plant Operation Authority, Compania Sevillana de Electricidad, respectively. Its success was due to the outstanding level of experience of all concerned in it, and particularly to the Construction Manager, John Hansen; the representatives of the Italian companies, A. de Benedetti and C. Sala from Agip S.p.A., and A. di Meglio from Franco Tosi Industriale; as well as the leaders of the Plant Operation Authority, F. Ruiz and J. Ramos. Thanks are due to all of them also for their contributions to this report, which I am sure will prove to be a very useful document.

The attached bibliography refers to documents with more detailed information on the subject.

Wilfried Grasse
SSPS Project Manager.

ASR CONSTRUCTION REPORT

CONTENTS:

ABBREVIATIONS

ASR - Advanced Sodium Receiver
AISI - American Iron and Steel Institute
CCTV - Closed Circuit Television

CRS - Central Receiver System
CRTF - Central Receiver Test Facility
DAS - Data Acquisition System
DCS - Distributed Collector System
DFVLR - German Aerospace Research Establishment
FAS - Flux Analysis System

HAC - Heliostat Array Controller
HFD - Heat Flux Distribution Measurement system
IEA - International Energy Agency
OA - Operating Agent IEA SSPS Project
POA - Plant Operating Authority (Compania Sevillana de Electricidad S.A.)
SSPS - Small Solar Power Systems Project

1 INTRODUCTION

1.1 ORIGIN

In 1979 Italy decided to contribute to the SSPS project, sponsored so far by eight members of the International Energy Agency. All major contributions to the project were by then already planned or contracted so it was agreed that Italy could participate by making a reduced membership contribution together with substantial in-kind contributions to both the CRS and DCS plants. The CRS contribution was to be an Advanced Sodium Receiver (ASR). The ASR should explore further the potential of sodium as a heat transfer medium and would have to reach the SSPS site and be installed so that some months of evaluation could be performed on this replacement Receiver during the Test and Operation phase planned to extend from 1981 to 1983.

1.2 OBJECTIVES

The principal objectives of the project were agreed to be:

a) To test the behaviour of the ASR for a period of at least six months within the Test and Operation Phase of the SSPS Project.

b) To enable the CRS Plant to run at higher heat fluxes and/or higher material and sodium temperatures.

1.3 PARTICIPANTS

The Italian contracting parties, (the Consiglio Nazionale della Ricerca - CNR and two companies) agreed to participate in the SSPS project as follows: The CNR would provide the membership contribution and the two companies would provide the ASR. The two companies would work as Contractors under the terms of a Contract agreed between:

DFVLR, as the SSPS Operating Agent (OA) and Snamprogetti Spa. and Franco Tosi Spa. as the Contractors.

The Contract included the provision for the DFVLR to retain Interatom GmbH. as their "Technical Representative" and; for the Contractors to use Ente Nazionale per l'Energia Elettrica (ENEL), and Ansaldo Meccanico Nucleare Spa. (AMN) as Subcontractors.

2 ASR PROJECT REALISATION

2.1 PROJECT ORGANISATION

2.1.1 Breakdown of the Work.

After the unanimous decision of the SSPS Executive Committee at the 9th SSPS meeting on 26 October 1979 to include Italian "in-kind" hardware contributions to the SSPS plants; the following tasks were agreed regarding the provision of the ASR:

PHASE 0: Contract Preparation. This phase involved the preparation and agreement of a contract between the two contractors and the DFVLR to provide and test the ASR in conjunction with the CRS plant. The contract would include agreement on: conceptual design, time schedule and milestones, interfaces, installation, test and evaluation plans in addition to the normal requirements for SSPS projects.

PHASE I: Detailed Design. This phase began with signature of the Contract and ended with the satisfactory conclusion of a formal Critical Design Review as specified in Annex C-1 of the contract.

PHASE II: Fabrication. This phase began after the acceptance of the final design and ended with the satisfactory conclusion of a formal Mechanical Completion Review.

PHASE III: Shipping, Installation, Testing, Acceptance. This phase included the shipping of the ASR to site; its integration into the CRS plant; and the start up and initial testing necessary prior to a formal Acceptance Review.

PHASE IV: Operational Testing. After Acceptance and Handover of the ASR to the Plant Operators this phase involves the conduct of routine operation and performance evaluations for at least six months but not later than the end of Stage 2 of the SSPS project.

2.1.2 DFVLR Organisation.

a) DFVLR controlled the activity from its office in Cologne until the completion of Phase II. From March 1983 the execution of Phases III and IV has been controlled by the DFVLR Almeria site staff.

b) Interatom has acted throughout the project as a Technical Consultant to the DFVLR. During phases I and II this co-operation was formalised by a contract whereby the DFVLR retained Interatom as his "Technical Representative" with responsibility for the technical execution of the project. The main activities were to be:

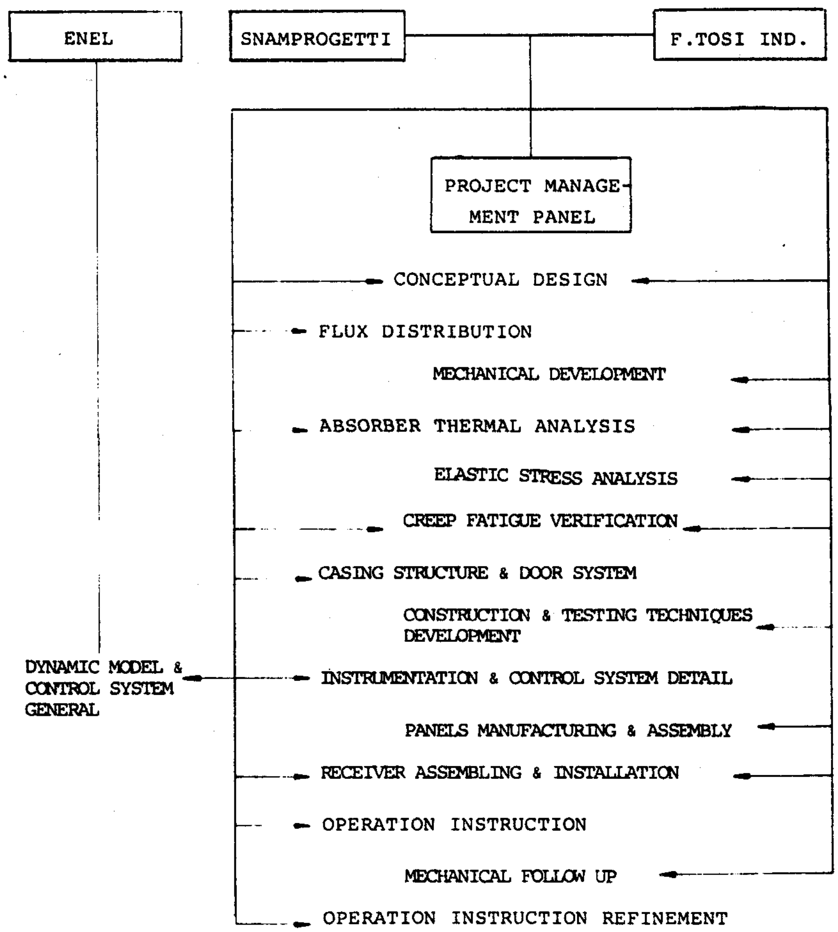
interface coordination
design approval
provision of CRS design data

The scope of work extended to include considerable participation with the contractors on the verification of the detailed tube bundle design and in the quality assurance of the ASR assembly.

c) DASAG Engineering (CH) were also retained by the DFVLR for a short contract during phase I to advise DFVLR specifically on: stress analysis, lifetime considerations, and detailed design provisions of the ASR tube bundle.

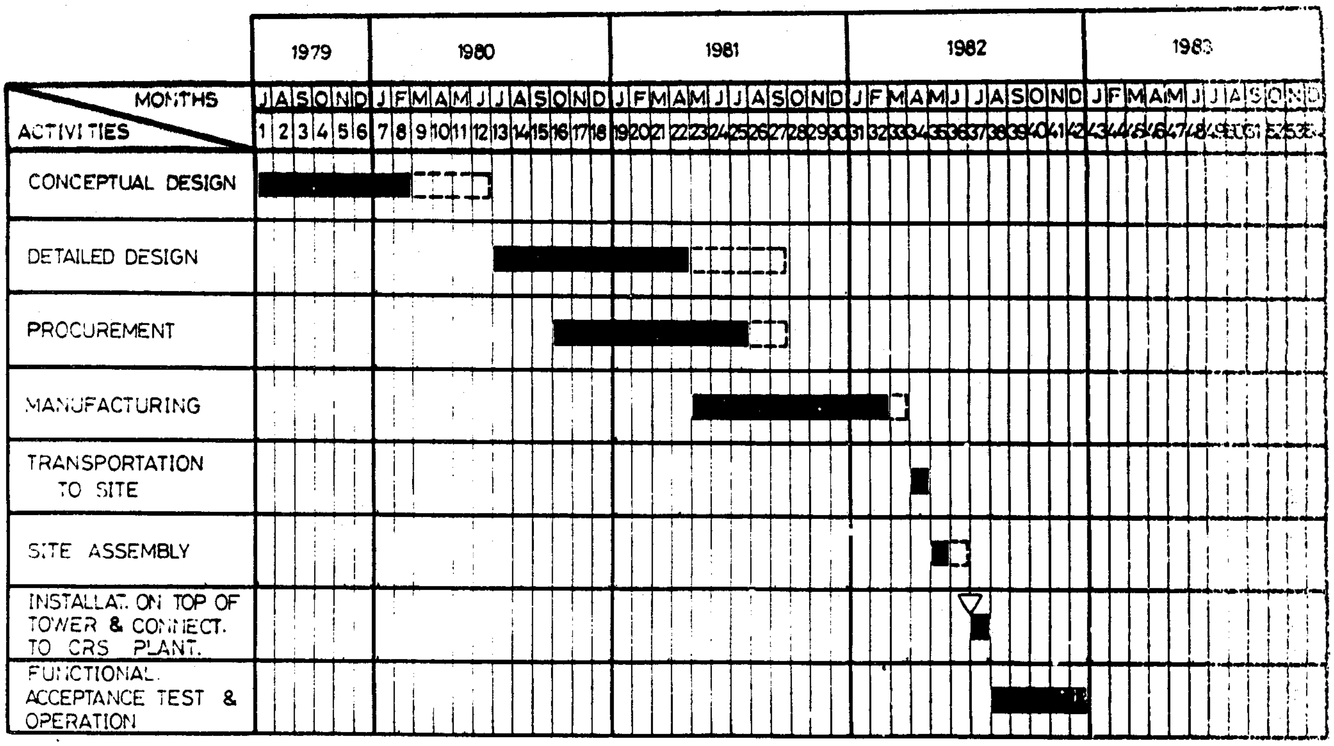
2.1.3 Contractors Organisation.

The contractors organisation during the various phases is illustrated below. Ansaldo did not participate in the ASR activities after the initial meetings in 1979.

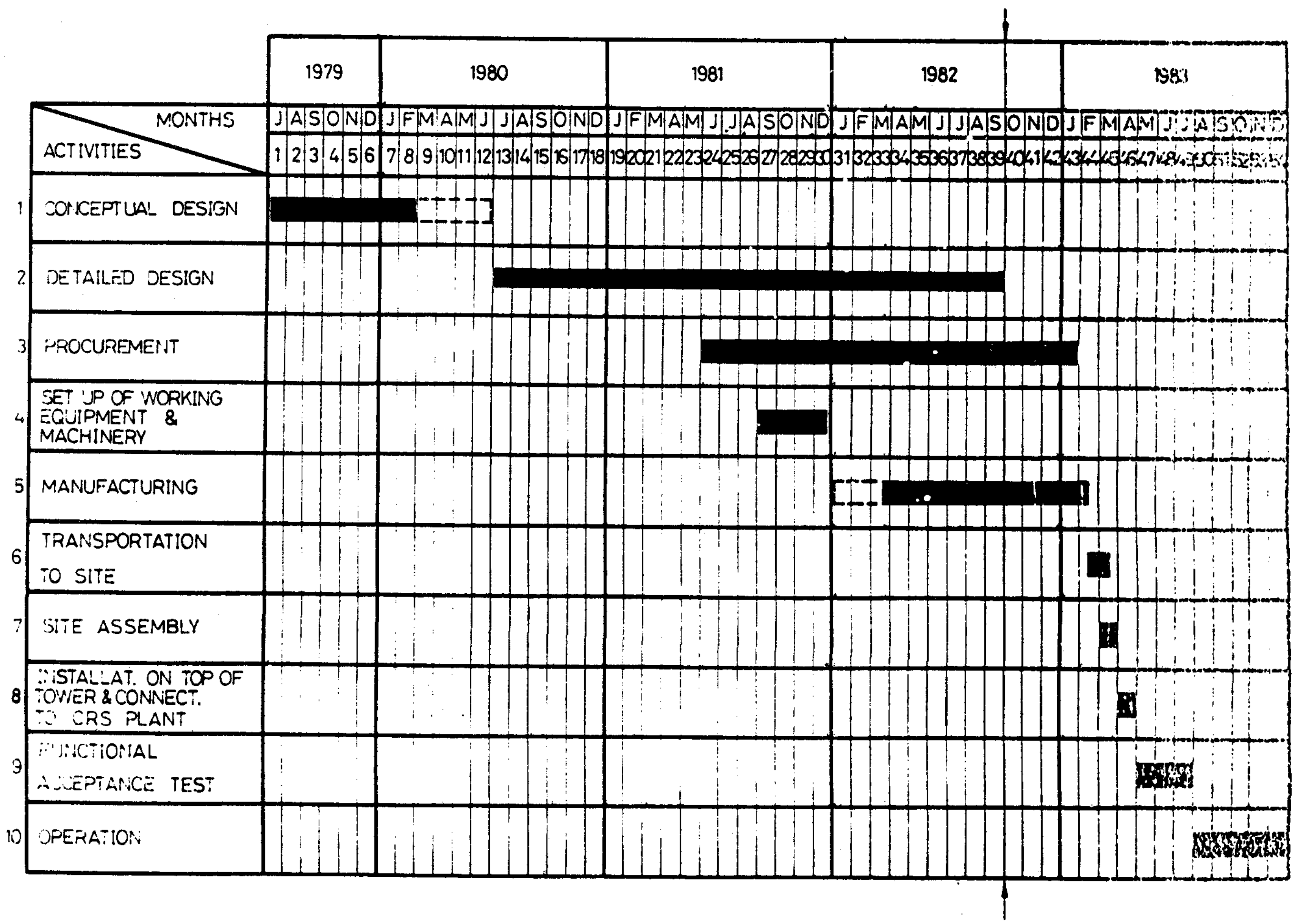


On 26.03.82 Snamprogetti were replaced by Agip Nucleare
On 01.01.81 Franco Tosi were replaced by Franco Tosi Industriale
On 01.01.84 Agip Nucleare were replaced by Agip

ASR SUMMARY SCHEDULE



ASR REVISED SCHEDULE



2.2 SCHEDULE AND MILESTONES

2.2.1 Milestones: The following milestones marked the end of each phase of the project:

PHASE 0 - CONTRACT SIGNATURE

PHASE 1 - CRITICAL DESIGN REVIEW

PHASE 2 - MECHANICAL COMPLETION REVIEW

PHASE 3 - ACCEPTANCE REVIEW

PHASE 4 - END OF EVALUATION/END OF SSPS PHASE 2

2.2.2 Time Schedules.

The project was extended several times due to organisational difficulties and due to extension of the technical investigations carried out during the design phases. On page 7 are shown revisions of the overall schedule incorporated in the contract and the contract change.

2.3 ACTUAL REALISATION

2.3.1 JULY - DEC.1979. Conceptual Design developed by the Italian partners. At this stage of the SSPS project two alternative CRS configurations were under discussion, one with a field of 160 Heliostats and a smaller version with 100. Two ASR alternatives were therefore considered with thermal inputs of 4.2 and 2.7 MW respectively. A wide range of receiver configurations were investigated of both cavity and external types, and with tube bundles incorporating straight, cross-over, and zig-zag tubes.

Conceptual design was sufficiently advanced in December 1979 to allow contract negotiations to begin.

2.3.2 JAN.- AUGUST 1980. Concept Finalisation and Contract Negotiations. The conceptual design was revised and refined until March 1980 in view of the latest information on heliostat field performance and the design ultimately installed was first outlined in April.

It was then possible to begin detailed design and to finalise the details of the contract. The ASR contract was finally signed by the Italian partners on 27/8 and by DFVLR on 12/9/1980.

The Contract included a deadline (15.12.80) for the agreement of the ASR size (4.2 or 2.7 MWth.) which remained unresolved. Detailed design was begun of both alternatives but such an effort could not be sustained for long. In view of the serious doubts regarding the risk to CRS objectives in case of problems with the ASR, the Contract also included the peformance of a Qualification test of a representative ASR element at the CRTF in Albuquerque USA.

2.3.3 SEPT. 1980 - FEB. 1982. Detailed ASR design.

a) In December 1980 the decision was made to go ahead on the basis of the smaller option, and design work was concentrated on an ASR for 2.8 MWth input power.

b) Detailed proposals were drawn up for the qualification testing of a single ASR panel at the CRTF(Albuquerque), to minimise the risks of unforeseen problems with the advanced absorber parts, but it proved impossible to organise a test in time. The possibility of a similar test using the SSPS CRS was then studied but it was eventually agreed that the alternative of a test at Almeria did not significantly reduce the risks to the CRS Stage 2 programme. Instead Qualification emphasis was transferred to the design work, increasing the work of the Contractors. The DFVLR and his technical advisers also increased their involvement in the ASR design and quality assurance procedures.

c) These considerations plus minor technical revisions resulted in contract change No.1, which altered the design conditions slightly, settled on the smaller power alternative, included the provision of a complete spare tube panel assembly and recognised some delay with a revised time schedule.

d) At a meeting at Franco Tosi, Legnano, in February 1982 it was agreed that design had progressed sufficiently to begin Phase II (fabrication), but numerous aspects of the desin remained under intensive study, particularly concerning the design of sliding supports and of welded connections to the absorber tubes.

2.3.4 MARCH 1982 - MARCH 1983. Fabrication and Qualification.

a) In addition to the construction of the ASR and spare panel, and rigorous quality control of the work, this phase included:
- Development of a detailed installation plan including removal and conservation of the existing receiver.
- Compliance with Spanish qualification requirements for imported machinery.
- Detailed interface design and planning.
- Preparation of draft operating documentation and proposed test and evaluation plans.

b) Agreement was reached on all remaining uncertainties at a meeting on site in September 1982 and final assembly of the ASR was authorised to allow a mechanical completion review in March 1983.

c) At a meeting in Legnano on 14/15 March 1983, a formal mechanical completion review was held to examine the:
- manufacturing quality assurance systems
- manufacturing data
- ASR installation plan
- to witness the final workshop inspections.

These reviews were succesful and agreement was also reached in principle on the functional testing and operation plans. It was agreed not to shut down the CRS operation until the ASR arrived on site due to the intensive evaluation of the original receiver, still in progress, and to the remaining uncertainties listed below:

- Incomplete electrical interface definitions.
- Outstanding agreements on site inspection and acceptance procedures involving Spanish authorities and the inspection agency.
- Incomplete qualification of the Spanish erection subcontractor.
- Potential shipping delays of the ASR and components.

2.3.5 APRIL 1983 - AUGUST 1983. Installation at Site.

The organisation controlling the work on site is illustrated on page 11.

a) The Italian contractors established their site office at the end of March and the ASR arrived on 27 April. The CRS was shut down on the 29th April, prior to the arrival of the remaining ASR components and erection equipment on 2 May. The spare panel reached the site in August.

b) Disconnection of the original receiver followed, together with assembly of the ASR support structure and preparation of the lifting equipment. The original receiver came down, the ASR went up and the auxiliary equipment was replaced on the tower from 22nd to end of May.

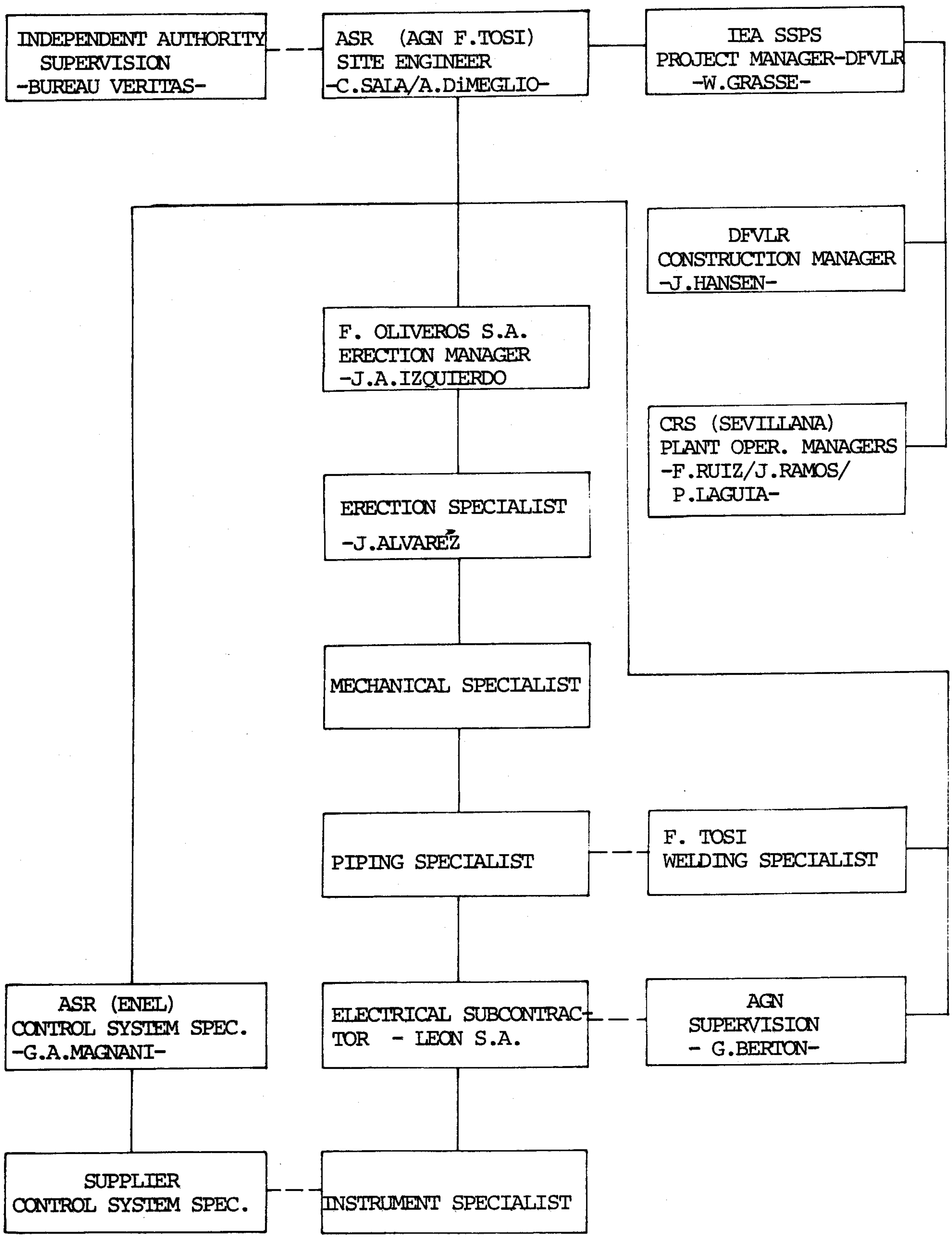
c) During June the sodium pipework and fittings were connected under the supervision of Bureau Veritas, along with the bulk of the instrumentation connections and the control system installation.

d) During July the microprocessor was started and the ASR control programs loaded. Operator training then began. On the tower work centred on trace heating connection and other electrical systems, pipe supports and insulation.

e) The first heliostat focused on the ASR on 5th August and the remainder of the month concentrated on functional testing without sodium and refinement of the heliostat aiming adjustments.

f) The preheating procedure was tested on the 24th August and the first filling with sodium took place the next day. Performance testing then began.

ASR INSTALLATION - SITE ORGANISATION



2.3.6 SEPTEMBER 1983 - DECEMBER 1983. Initial Testing.

a) Early in September, after 24 hours of operation at reduced power and temperatures, the ASR was drained to allow further finishing work on the tower. During the subsequent preheating and refilling a defective trace heating element caused a flow blockage in the main downcomer sodium pipe causing conditions that led to unacceptable deformation of some absorber tubes. The ASR was then drained and testing delayed until the completion of a thorough technical investigation.

b) Early in October the deformations were corrected in situ by Franco Tosi specialists and the checking of a new preheating and filling procedure begun. The ASR was refilled again on 10th October and functional and acceptance testing resumed.

c) Acceptance testing was completed satisfactorily on December 15 and an Acceptance Certificate issued by DFVLR valid from that date. The ASR was then handed over to the Plant Operating Authority and the Test and Evaluation Phase began.

Although the ASR was accepted, several improvements and modifications had been decided upon as an indirect result of the investigations after the September filling incident. These remained to be done, namely:

- Installation of individual vent valve controls
- Connection of 18 thermocouples to the DAS.

In addition, a problem with the control system remained, concerning the tuning of the response of the sodium circulating pump, and the improvement of Sun Presence sensor signal characteristics. This problem restricted ASR operation to clear days only, free of the risk of sudden cloud transients.

2.3.7 JANUARY 1984 on. Operation and Evaluation.

The outstanding modifications were implemented steadily as materials became available and technical problems were resolved.

The sodium pump control response was modified in January, but the system still needed new software to revise the sun presence sensor signal used by the ASR control system.

The vent valve control modification was made in April. At the same time the additional DAS connections were made.

Contracted Design Conditions

Incident power:	2,7 MWth. (equinox noon, at design insolation)
Efficiency:	0.88 +/- 5%
Configuration:	external, flat, vertical
ASR position:	active surface on aiming plane, centre at X=0m,Y=0m,Z=43m.
Aiming strategy:	3 point aiming (see below)
Incident heat flux peak:	1,38 MW/m (=2,75 mrad)
Average incident heat flux:	0,32 MW/m
Average to peak flux ratio:	0,29
Sodium inlet temperature:	270 C.
Sodium outlet temperature:	530 C.
Flow rate:	7,3 Kg/sec. (design power)
Design pressure:	6 bar
Pressure drop:	1.2 bar

Active surfaces:

8.32m area, 2.92 m width, 2.85 m high.
5 equal panels, series connected
41 tubes each panel (0.578 m width)
tubes(O.D.14 mm,
thickness 1 mm.)
sodium velocity 1.8 m/s (design power)
tube material SS AISI 316 L
maximum tube temperature 600 C.

3 ASR DESIGN

Conceptual design of the ASR coincided with the manufacture of the original CRS plant and the conceptual design was agreed just before installation work began on site in Almeria. Throughout the design phase therefore, the reference data was refined or changed as the final form of the heliostat field was fixed and its actual performance became known.

3.1 BASIC DESIGN

3.1.1 The design objectives were:

a) To operate at flux levels approximately double those of the original receiver. The agreed targets were:

Peak incident heat flux 1,380 kW/m^2(Cavity 620)
Average incident heat flux 320 kW/m^2(Cavity 160)
at the design condition (920 w/m^2, equinox noon).

b) To provide a structure which could be regarded as a model or a module of the absorbing surface of possible large future commercial receivers.

c) To provide a working life of at least 10 years routine operation.

3.1.2. BASIC CHARACTERISTICS

a) With the absorber area roughly determined by the average flux target, the shape was determined by a compromise between spillage and losses, and the border thermal conditions to be 2.75 by 2.85 m.,area 8.32 m2. The absorber tube configuration was derived from stress and lifetime analysis.

b) The flat, vertical external configuration was chosen to give the required flux levels and to conform with objective b) regarding potential for upscaling.

c) Thus resulted the basic design conditions shown on page 13 as agreed in the ASR contract for the baseline specification for the ca. 2,7 MWt ASR. (The detailed design of the ASR would be based on final heliostat field layout and performance data).

d) The evolution of the basic design is further detailed in Progress Reports 1, 2 and 3, prepared by the Italian participants from October 1979 to May 1980.

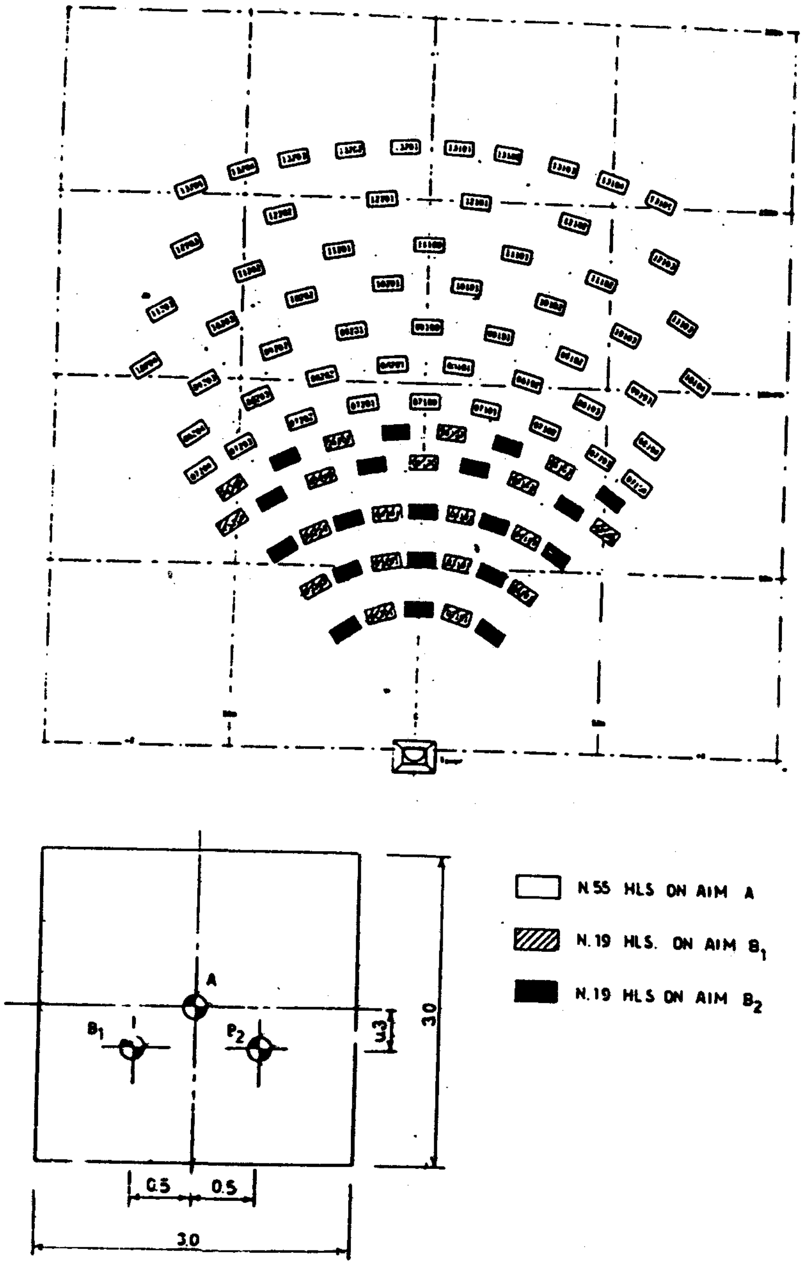


FIG. 1 HELIOSTAT FIELD AND AIMING STRATEGY

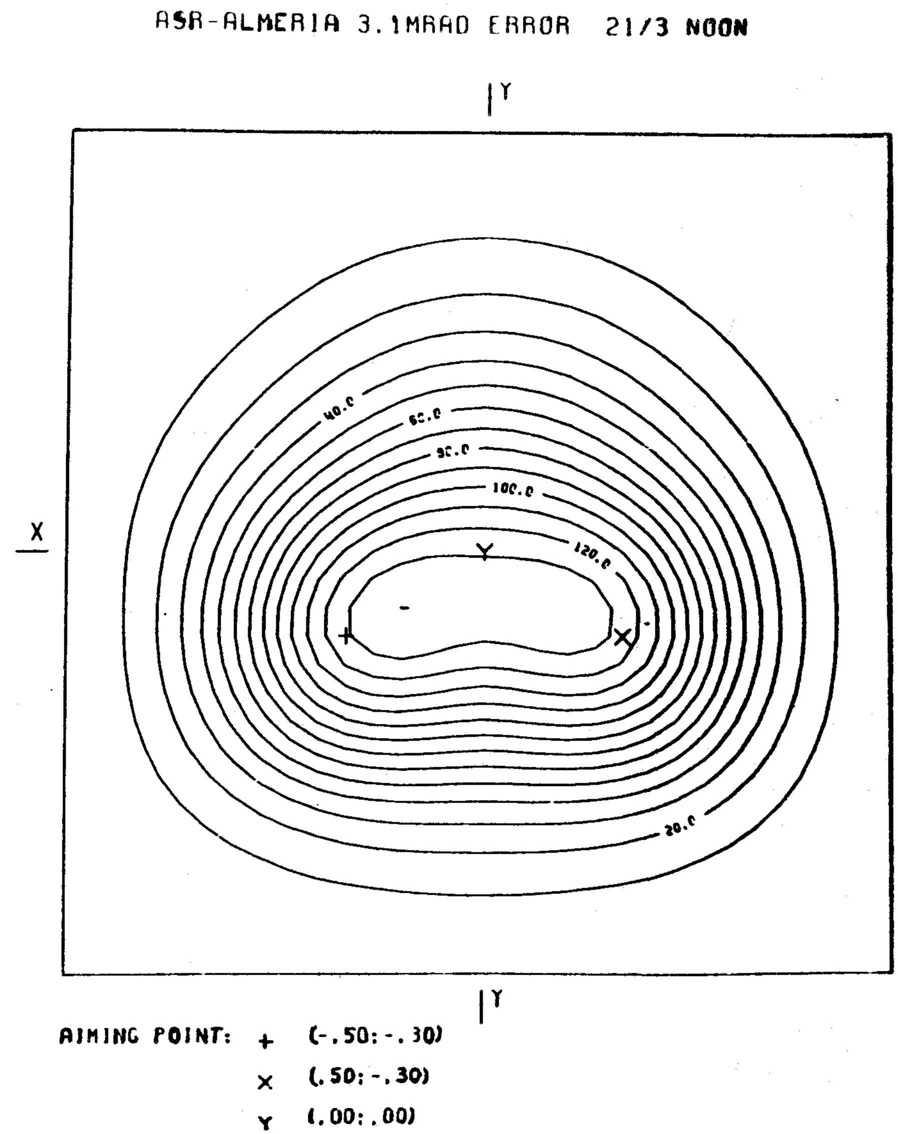


FIG. 2 EQUIFLUX LINES, SPACING (W/CM2) 10.0

3.2. MAIN INVESTIGATION AREAS

3.2.1. Incident flux distribution

a) The aim of the work was to accurately define the thermal input from the heliostat field and to develop a heliostat aiming strategy with the best compromise between spillage and uniform flux distribution. The work had to be revised during execution to cope with corrections to the assumed heliostat accuracy and a decision to raise the ASR (1m) to suit pipework installation.

The work also included a full treatment of the flux distribution transient resulting from a cloud passage.

b) The work was done by computer-aided analysis using a specially adapted version of the Helios programme. A satisfactory three point aiming strategy was developed and the thermal input adequately defined for stress analysis and lifetime design work (see page 15).

3.2.2. Absorber thermal analysis

This work involved the analytical determination of the steady state temperature distribution of the ASR absorber panels. The work included allowance for the following calculated losses: reflection of incident flux, IR radiation from the hot surfaces, convection, and conduction through the backwall insulation.

Several analyses were performed for different solar conditions and consequent different sodium flows. As a result performance characteristics were developed of efficiency and losses against power level.

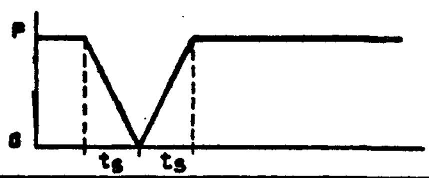
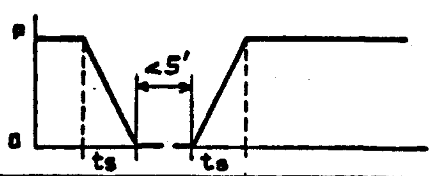
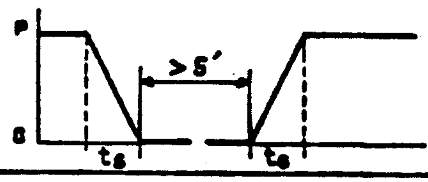
3.2.3. Tube panel stress analysis

a) This work analysed the stresses in the three alternate configurations of absorber tubes in order to validate the tube design, to detail the stresses involved and to ensure that the design chosen complied with the applicable code limits under the contracted conditions of service.

b) The operating pattern of a typical year was forecast to be:

- 327 Operating days
- 50 Cold start ups (after preheat and fill)
- 277 Warm, morning starts
- 3000 hours operation
- 327 Normal shut downs
- 6325 Cloud transients (see table below)
- 18 Emergencies
  - 6 pump control failure at full load
  - 6 pump control failure at part load
  - 6 power failures

The work considered the effects due to thermal heat flux and the mechanical loads during the operation predicted above. After a thorough preliminary analysis the most stressed tube was considered (the hottest tube) and detailed work was concentrated on that.

TYPE		CLOUD VELOCITY (Km/h)	10	23	50
		t_s (sec)	54	24	11
a	1		1000	1000	1000
	2		1000	1000	1000
	3		150	150	25
			2150	2150	2025

CLOUD PASSAGE TRANSIENTS (PER YEAR)
(P= PEAK INCIDENT FLUX
Σ EVENTS =6325)

c) The temperature distribution was determined using a finite element calculation programme (FLHE of the BERSAFE series). Stresses were then derived by finite element analysis (SAP 5 structural analysis code). The following aspects were then considered for code compliance: bursting, shake down, ratchetting, creep-fatigue.

d) The analysis was claimed to be conservative due to the following assumptions:
- elastic analysis was applied.
- creep in compression was assumed to be as dangerous as creep in tension.
- creep-fatigue verification considered relaxation fatigue to be as dangerous as creep fatigue.

e) Inelastic analysis of the most stressed section was performed (MARC CODE) considering the real material behaviour at the high thermal stresses beyond the yield point. A generalised plain strain analysis was used to find the reference strain range for cycling.

f) The analysis was repeated several times until it was agreed by Interatom that all critical design details applying actual state of the art design codes used in nuclear technology were satisfactory. The lifetime estimate based on elastic computations of more than 6000 cloud transients per year was agreed to be conservative but some concern remained over fatigue usage factor and creep damage. Computations based on inelastic analysis had fully demonstrated the required lifetime.

3.2.4. Detail of absorber connections to headers and intermediate supports.

a) The most critical part of the detailed design was the design of the four intermediate "stirrup" supports welded to the absorber tubes to support them in the span between the upper and lower headers. The design of the welded connections of the absorber tubes to the headers was also crucial.

b) A detailed stress analysis was conducted and the compliance with the relevant codes evaluated. These activities were monitored and separately checked by the DFVLR's technical consultants.

3.2.5. Development of a dynamic model for operation simulations

a) This work involved the development of computer models to dynamically simulate the ASR and the primary sodium loop, and the control system loops. The model should give the temperature distribution in the ASR metal and sodium under the following predicted conditions: steady state operation, normal operational transients (cloud passages), emergency conditions (pump or control failures).

The results were required for control system design and for the stress analysis studies.

b) Two models were used: a simulation non linear model based on first principles and accounting for the distributed nature of thermo-hydraulic phenomenae, and a linear model.

c) The linear model is suitable for all full range simulations needed for control verification, receiver life analysis, and operating procedure assessment. The subsystems considered in the model are: radiated tubes, connecting tubes, headers, sodium pump and pump motor.

d) The second model evaluated the transfer functions needed for the control system design. The system equations have been linearised about an equilibrium point, transformed and integrated with respect to space to yield the desired relationships between the sodium temperatures (at any point), the sodium flow rate and the incident heat flux.

e) The simulation non linear model is now installed on the VAX 11/730 at site and is used for experimental transient simulation.

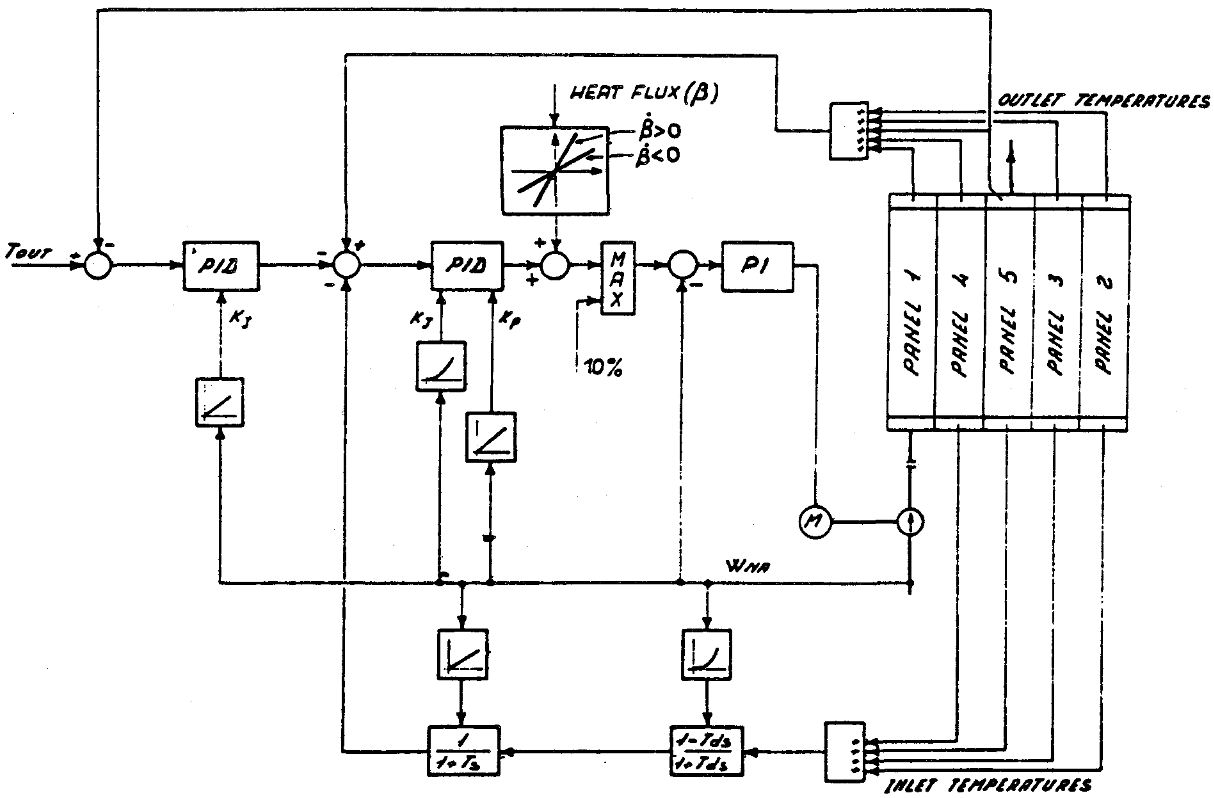
3.2.6. Control system design

a) In principle this work involved the design of a system to control the flow of sodium according to the variation of the absorbed thermal power to maintain a constant outlet temperature. As no accurate signal of the incoming power is available a sufficiently sensitive feedback signal, derived from panel temperatures, had to be developed that could be used in conjunction with the sun presence sensor signal to control the sodium pump speed.

b) A system of three cascaded loops was developed. The intermediate loop reacts to a complex function of the panel inlet and outlet temperatures. The sun presence sensor signal gives a crude feedforward indication; metal temperatures at the back of some irradiated tubes close to the outlet are used to give an additional speed-up of the system.

c) By simulation the system was proved to be stable and able to control the ASR through all foreseen transients. It was also verified that manual control was impossible during the foreseen cloud transients.

A schematic of the selected system is shown below:



ENEL - DSR - CRA

3.2.7 Backwall Development.

Considerable attention was paid to the design of the backwall behind the absorber surface and the choice of suitable materials, between ceramic and fibre. After analysis of the possible energy passing between the absorbers to the backwall it was decided that the use of fibrous material was too uncertain in spite of the attractions of the potential savings of weight and thermal inertia. A specially formulated ceramic was then defined, and the wall positioned to allow acceptable operating temperatures.

3.2.8. Structure analysis

Detailed analysis was also carried out for the following components:

a) Piping System. Detail stress analysis was required to ensure that the arrangement selected was suitable for the transient operation conditions. Some difficulty was experienced in the design of the absorber panel tube connections to provide adequate flexibility for thermal conditions.

b) Upper and Lower Headers. Detail analysis was again required to ensure that thermal transients would not impair the design life.

c) Receiver Structure. The design of the structure is based upon cold operating conditions, implying stringent insulation. The contractual requirements for environmental loads were fully investigated.

More detail of these investigations can be found in SSPS Technical Report 3/83 which collects all the Italian Topic Reports into one publication (two volumes).

3.3. FINAL CONFIGURATION

3.3.1 Performance Characteristics.

At the design point operating condition the following conditions are expected:

	Incident Power	2750	KW
	Absorbed Power	2450	KW
Losses:			
	reflection	138	KW
	convection	82	(wind 5 m/sec)
	emission	80	
	Total	300	KW
Average incident flux		35	W/cm
Maximum incident flux		138	W/cm
	(see table on page 22)		
Sodium:	inlet temp.	270	C
	outlet temp.	530	C
	flow rate	7.3	Kg/sec
	Pressure drop	1.2	bar

ASR-ALMERIA 3.1MRAD ERROR 21/3 NOON

E. (left) — W. (right)

,08	,27	,55	1,20	1,75	1,98	1,74	1,20	,64	,26	,08
,30	,93	2,26	4,30	6,38	7,28	6,36	4,28	2,25	,93	,29
,77	2,48	6,22	12,2	18,6	21,4	18,6	12,2	6,20	2,49	,79
1,58	5,41	14,3	28,5	43,3	49,7	43,2	28,5	14,3	5,47	1,65
2,63	10,2	29,3	58,1	82,3	90,7	82,1	57,9	29,2	10,3	2,76
3,45	15,5	50,4	99,3	126,	129,	125,	98,4	49,9	15,6	3,64
3,46	17,1	59,7	117,	138,	132,	136,	115,	59,1	17,3	3,68
2,62	12,7	42,7	81,6	94,4	89,6	93,5	80,7	42,3	12,9	2,53
1,43	6,06	17,8	32,2	38,7	38,6	38,5	32,1	17,6	6,24	1,60
,53	1,67	4,62	8,00	10,4	11,1	10,4	8,04	4,71	1,98	,62
,13	,40	,91	1,60	2,22	2,48	2,22	1,60	,94	,43	,15

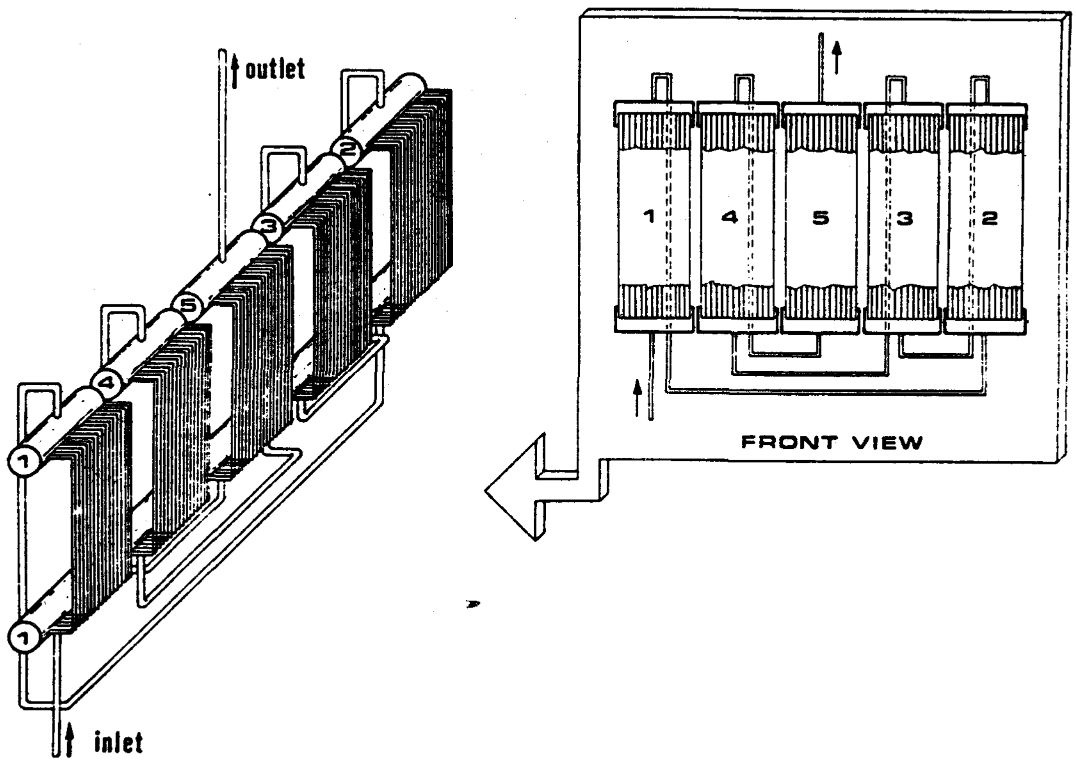
BOT.

HELST. NO.	93,	AIM. NO.	3,
INSOL. KW/M2	,920	STD.DEV. MRAD.	3,10
DAY NO.	80,	INC.POW. KW	2870,
TIME HR.	12,	AVERG./PEAK	,23
TOWER HEIGHT M	44,	SPILLAGE %	,12
TARGET DIM. M	3,0X3,0		

FIG. 1.2 INCIDENT FLUX ON FLAT TARGET (W/CM2)

3.3.2 Absorber Configuration.

a) The absorber surface consists of five identical tube panels as shown.



The panels are connected in series so that sodium flows upwards through each one, first through the outer panels in the low flux areas and finally through the hottest centre panel, in order to minimise losses and give the optimum control response.

b) Absorber data:

Absorber	Width	2785 mm
	Height	2850 mm
	Area	7.937 m
Number of panels		5
Panel Width		555 mm
Tubes per panel		39
Tube	Diameter	14 mm
	Thickness	1 mm
	Material	AISI 316L
	Coating	Pyromark 2500

c) With these dimensions and a sodium velocity of 1.9 m/sec a maximum tube wall metal temperature of 596 C is reached in the most irradiated section of the centre panel being cooled by sodium at 495 C.

3.3.3 Structure. The figure on page 25 shows the ASR structure supporting the absorber. The structure comprises:

ASR Panel assembly	- 7800 Kg
Aperture Frame	- 1330 Kg
Door Assembly	- 2600 Kg
Support structure	- 8000 Kg

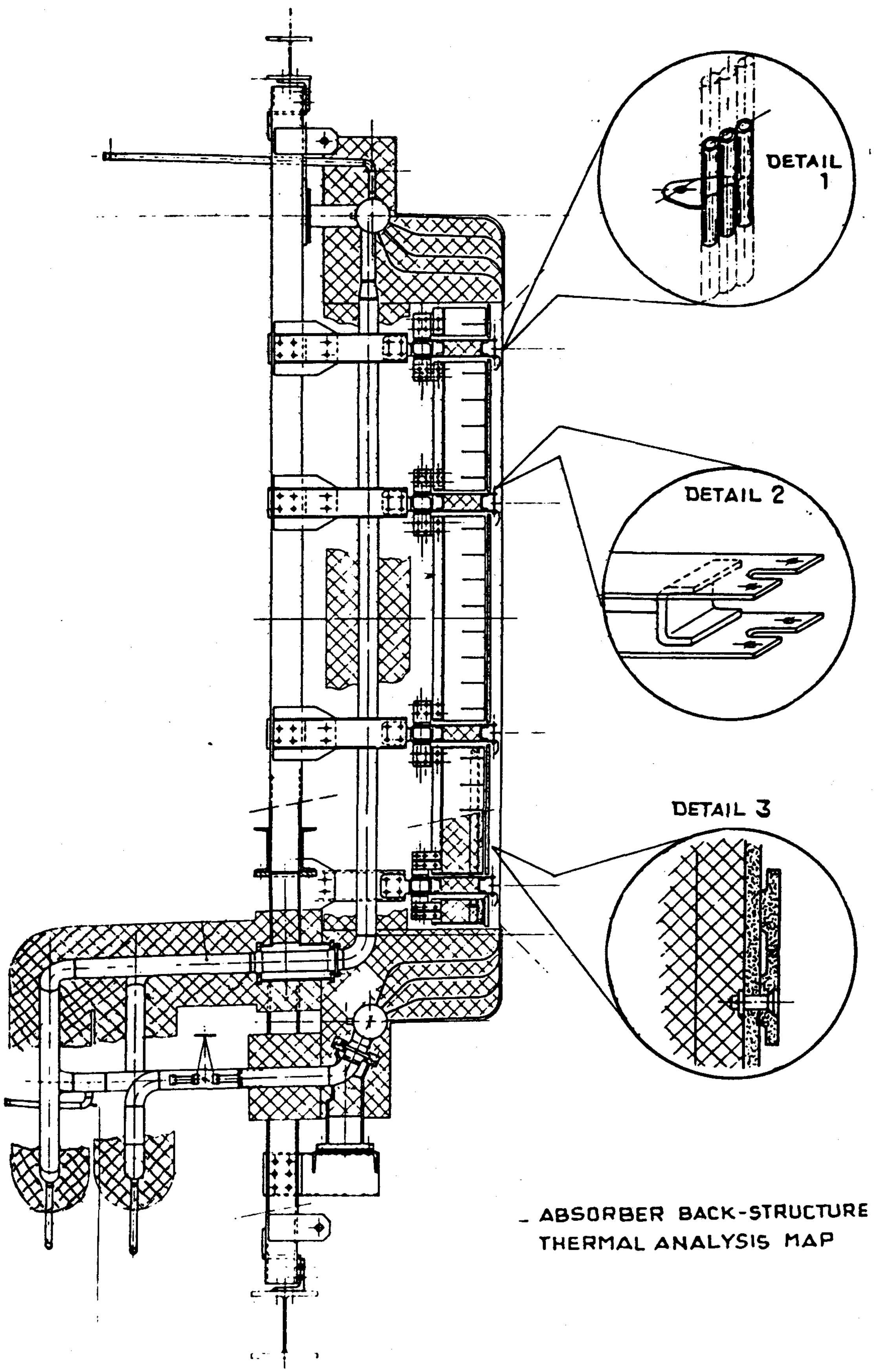
a) Each panel of absorber tubes is part of a complete modular panel assembly, including sodium pipework, backwall insulation, and the supporting structure. Each panel weighs 1450 Kg . The ASR consists of 5 of these identical modules mounted side by side in a box structure bolted to the top beams of the CRS tower. In front of the structure is fitted an aperture frame and then the doors structure.

b) The sodium wetted parts of the panel modules are the bottom header, the absorber tubes, the upper header and the downcomer pipe. The system is attached to a fixed support at the inlet flange of the bottom header. The absorber tubes are fixed together in groups of three (13 "triplets" per panel) by welded on support plates at four levels up their span. These plates are connected to the panel structure by the "stirrup supports" which allow considerable vertical movement up and down the support pin and some rotation and lateral movement due to the clearance of the pin hole in the plates. The upper header is supported to allow vertical sliding and the downcomer is restrained at the outlet flange. All the sodium tubes and the triplet support plates are of the same material.

c) 45 mm behind the absorber tubes is the ceramic backwall. The wall is made of a double layer of overlapping "mullite" tiles. The tiles are fixed with pins of the same material.

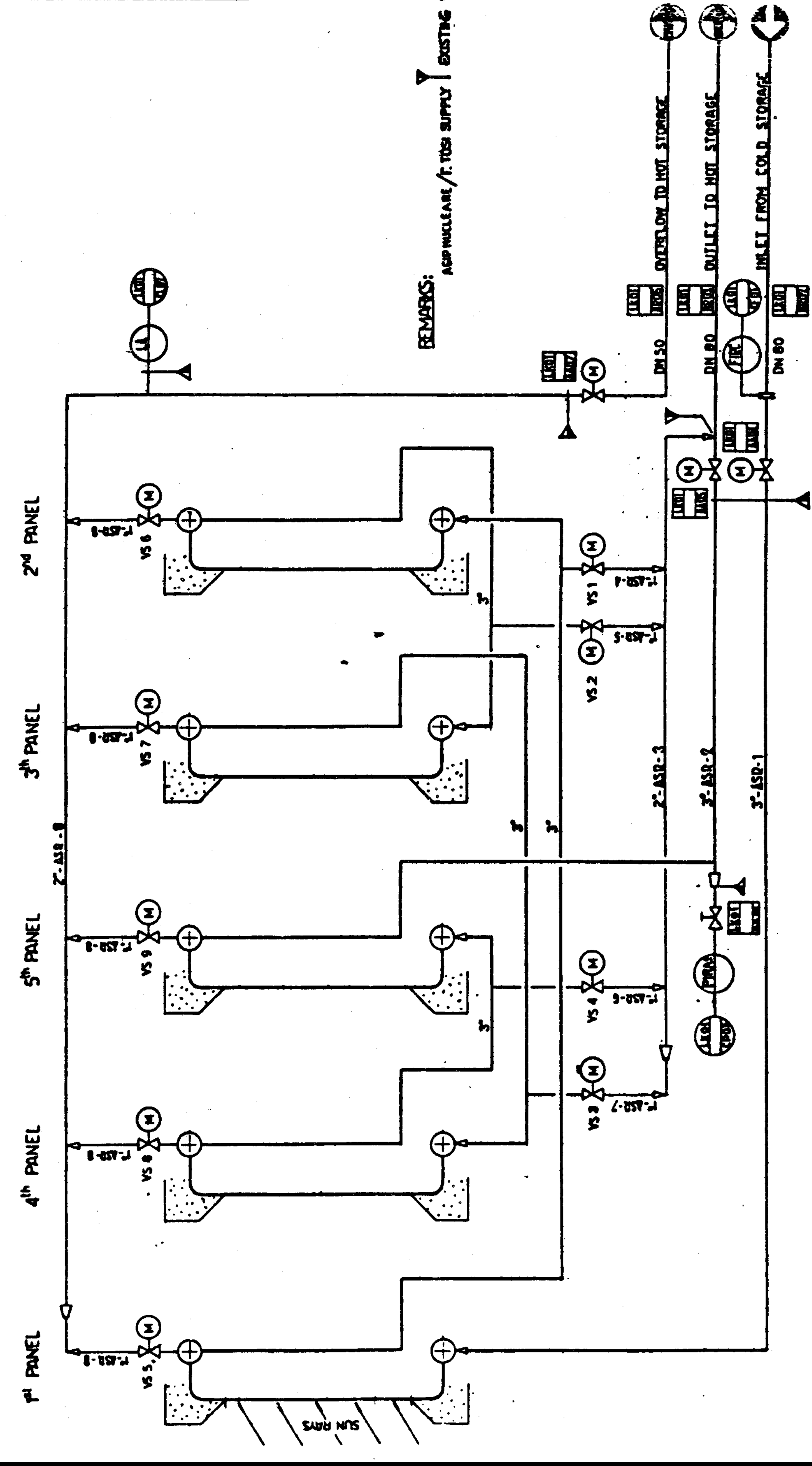
This high refractory alumina material can withstand surface temperatures to 1850°C. Absorber deformation to give a gap between tubes of up to 3 mm is anticipated and would result in peak ceramic surface temperatures of 1200°C.

Interstices are closed with ceramic fibre felt, and behind the wall is 175mm of ceramic fibre insulation to minimise incident energy reaching the support structures, and losses.



- ABSORBER BACK-STRUCTURE THERMAL ANALYSIS MAP

ASR FLOW DIAGRAM



d) The aperture frame provides a bevelled ceramic border 260 mm wide around the absorber face. The border is constructed of the same tile system as the backwall. Outside the ceramic border the frame is faced with AISI 316 sheet for a further 375 mm. Behind the facing is 130 mm of ceramic fibre felt.

e) Two sliding doors 4.3 m high, 2.2 m wide are mounted in a simple frame to close 600 mm in front of the absorber. The doors are driven by single speed geared motors with provision for hand cranking, and are controlled by endswitches. Each door (weight 800 Kg) is 310 mm thick and consists of a steel frame faced all over with AISI 316 sheet and filled with ceramic fibre. The doors are coated on the outside with white pyromark.

f) The ASR assembly is mounted to a box structure which supports and encloses the ASR, houses instrumentation and control cabling, supports the sodium pipework, venting and draining systems and provides a mounting platform for the CRS tower auxiliary systems (CCTV, crane, air warning lamp, lightning conductor, HFD instrumentation, emergency beacon).

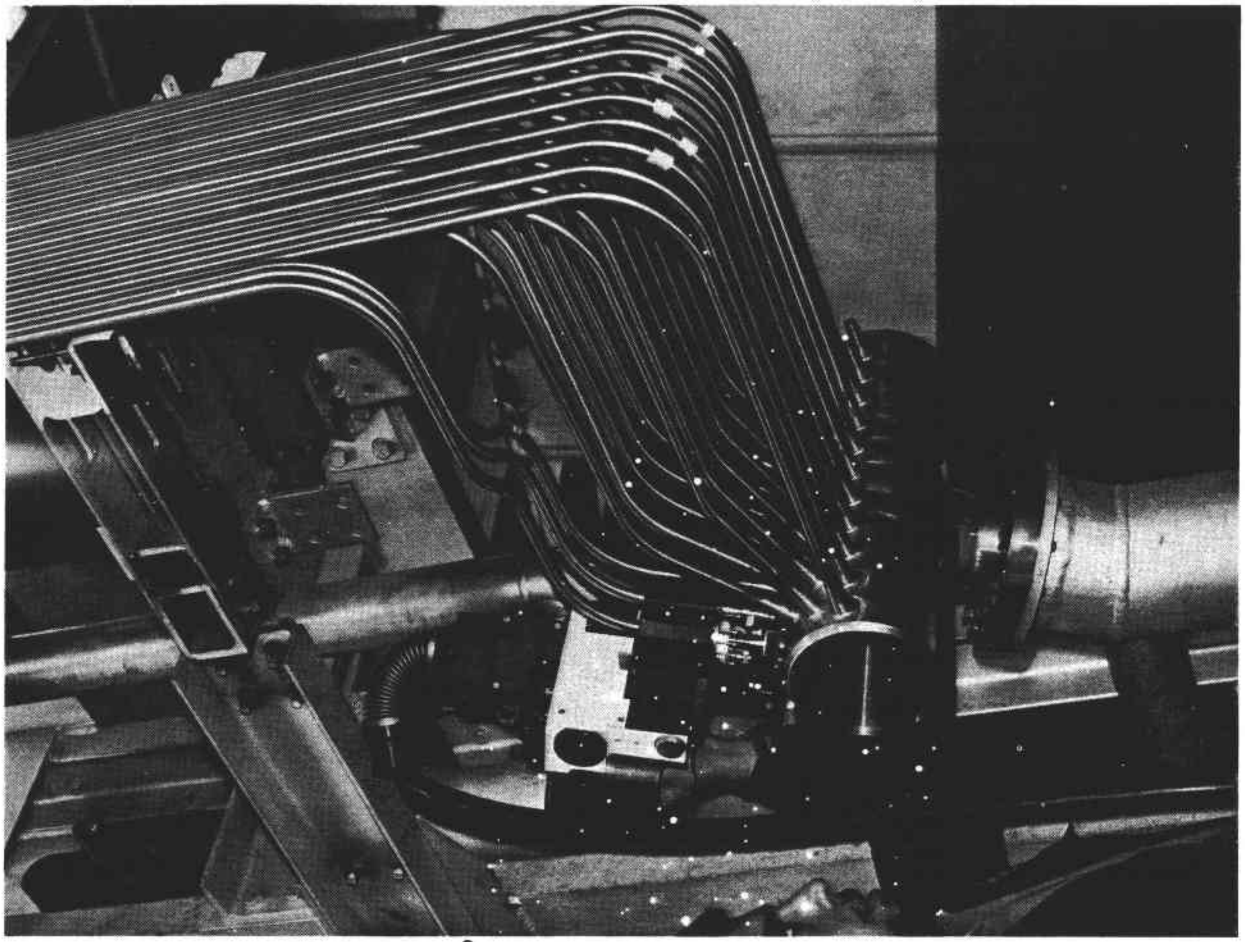
3.3.4 Sodium Circuit.

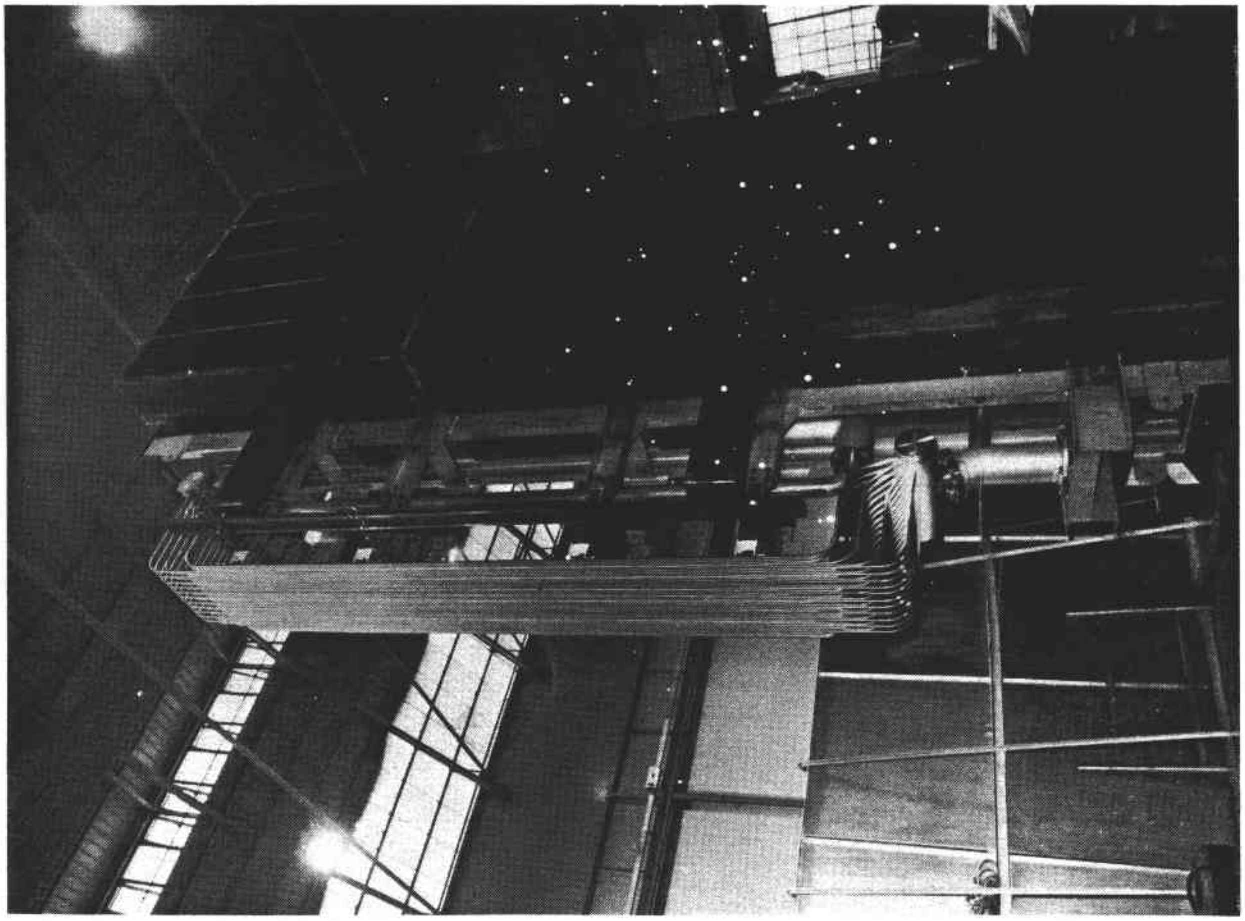
The design of the system is illustrated by the flow diagram on page 26.

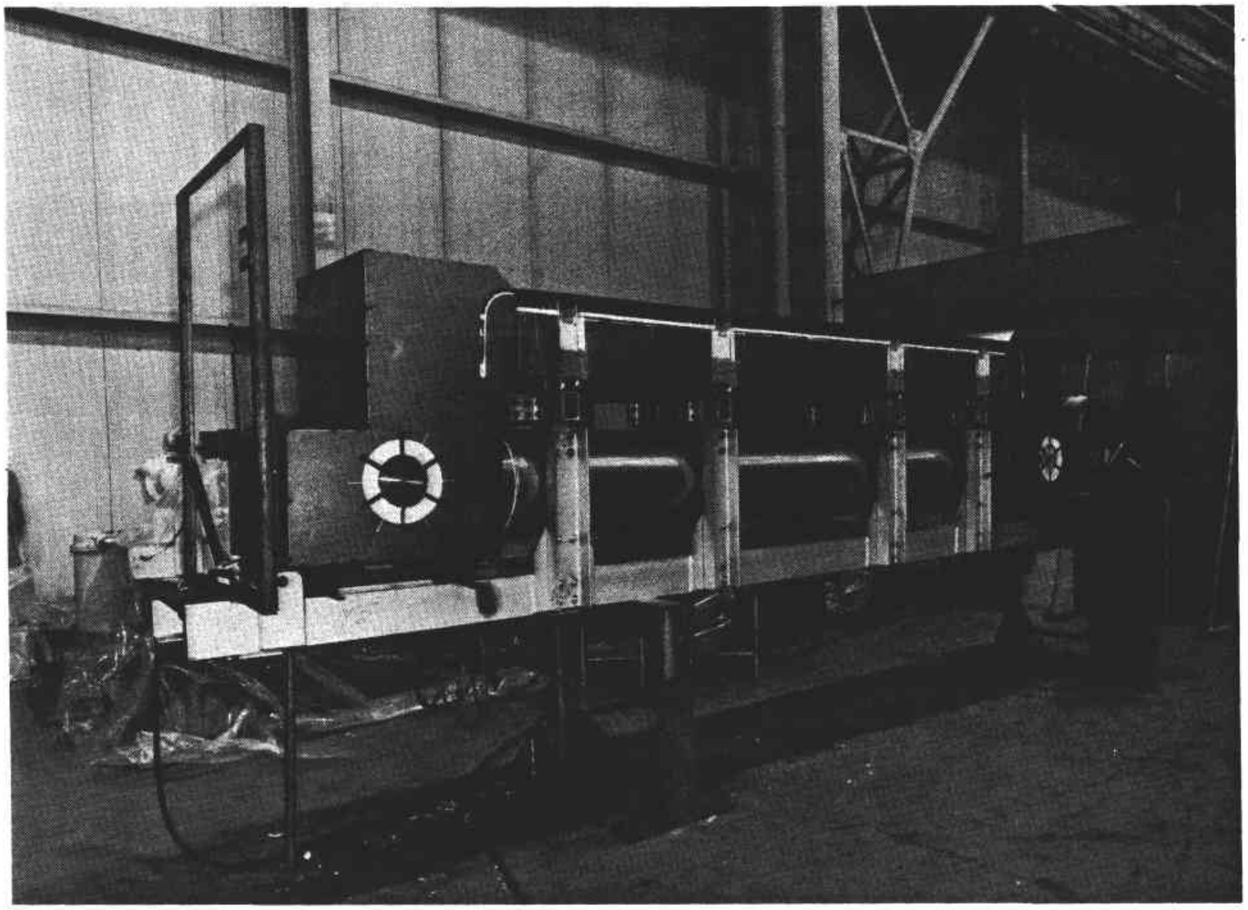
a) The diagram shows where the main 3" circulating pipes are connected to the original circuit and how the original stop valves, level sensor and sodium detector are reused in the new system. All the new fittings are built and installed to the same standard as the original system.

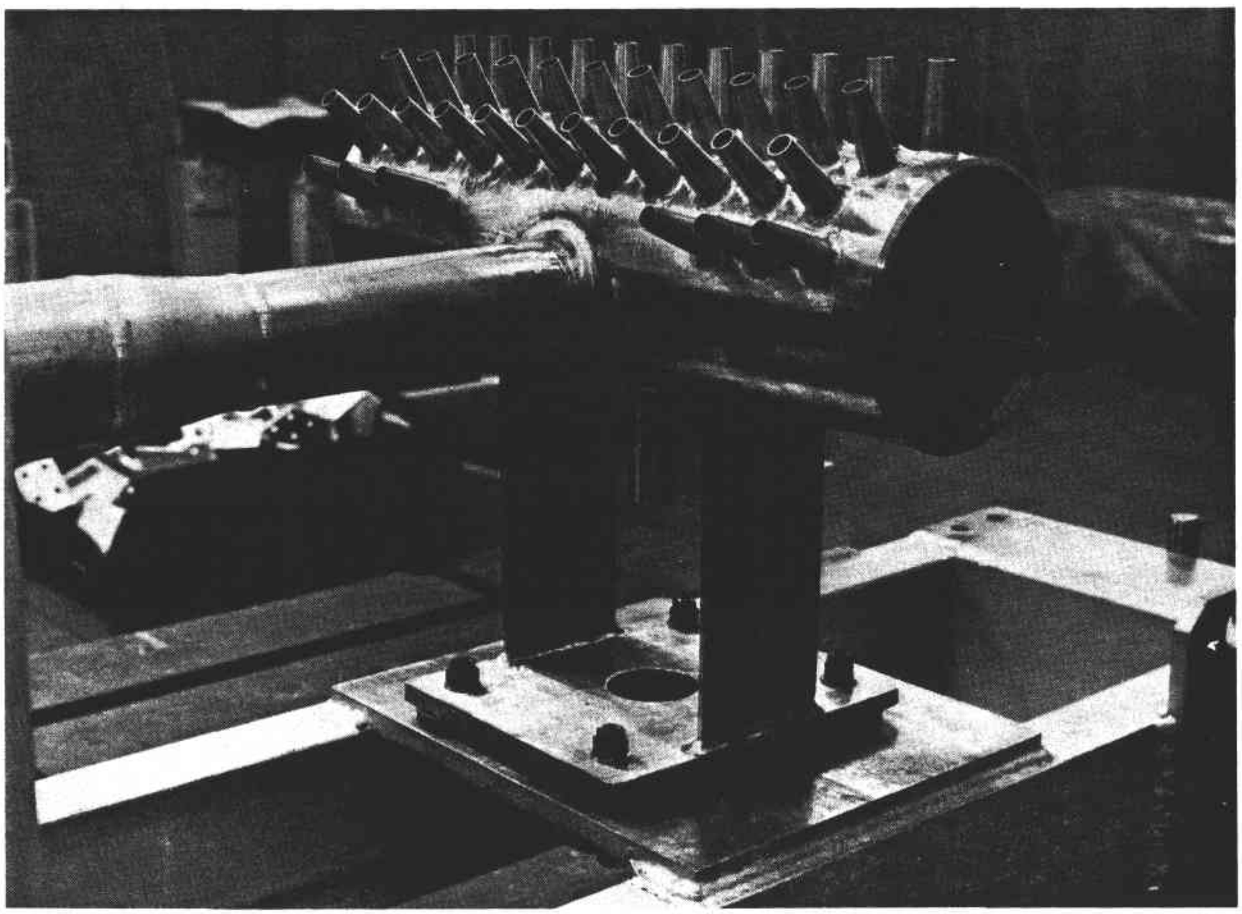
b) Individual motorised vent valves are fitted to the top header of each panel, and these are then connected to the original vent system before the original vent valve which can now be used for double shut off.

c) Individual motorised drain valves are fitted to the latter four panel bottom inlet connections and are led to a new connection downstream of the main outlet valve on the downcomer to the hot storage. The first panel is connected to drain through the inlet upcomer from the cold storage. The vent and drain components are also identical to the original equipment.





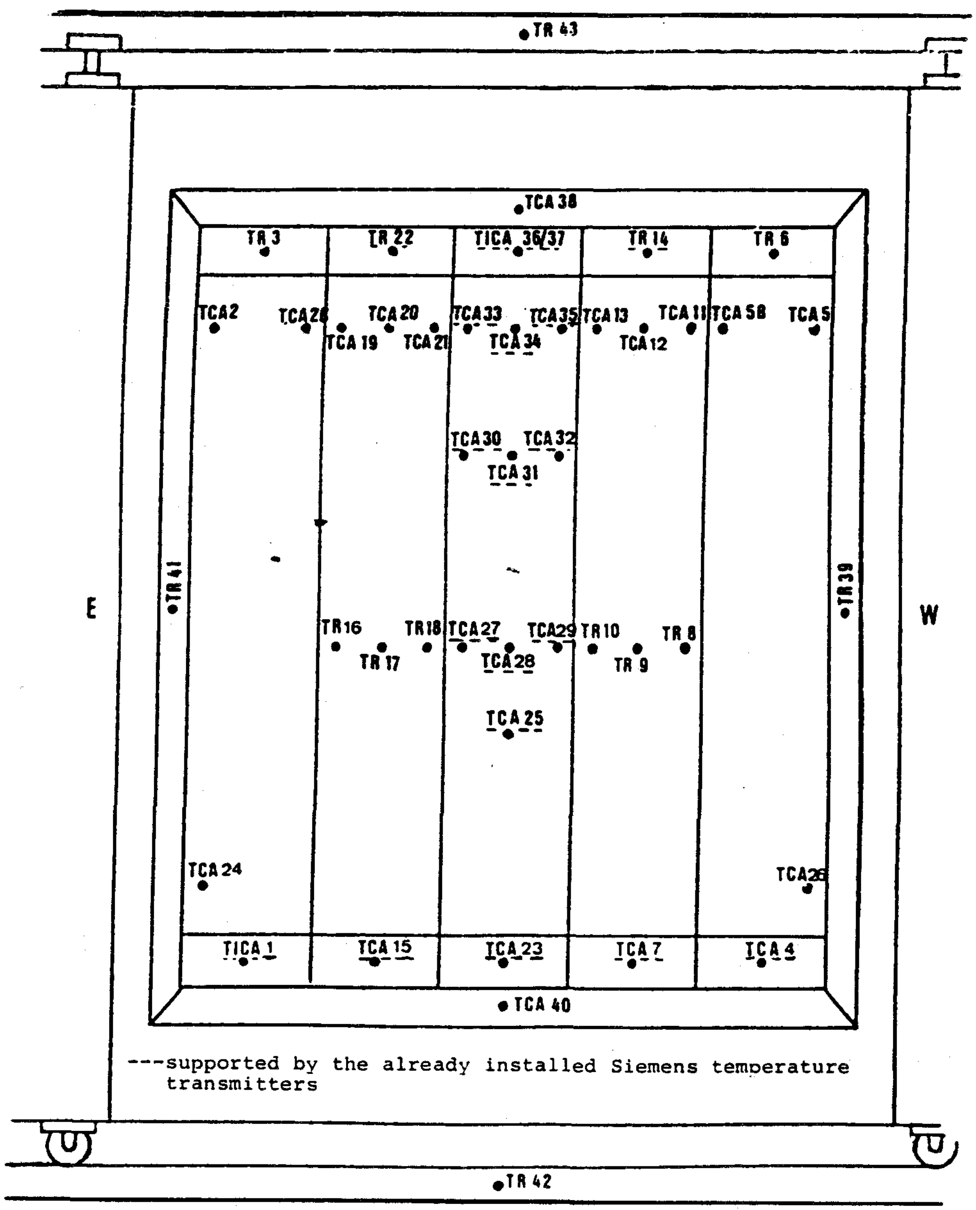




3.3.5 Instrumentation.

a) The location of the temperature measurement sensors is shown on the figure below.

Thermocouples on ASR tube bundle.



---supported by the already installed Siemens temperature transmitters

Of these sensors 19 were originally connected to the original DAS replacing the original instruments as listed below. All the above sensors are connected to the new ASR control and data display system.

Thermocouple tag changes:		
Location	original tag	ASR tag
tube	CT03	TICA 1
	CT04	TCA 30
	CT05	TCA 31
	CT06 **	TCA 35
	CT07 **	TCA 33
	CT08 **	TCA 34
	CT09	TCA 32
	CT10	TCA 27
	CT11	TCA 28
	CT12	TCA 29
	CT13	TCA 25
	CT14	TR 22
	CT15	TCA 23
border	CT25 **	TICA 36
	CT26 (SPARE)	TICA 37
	CT28 *	TCA 23
	CT29 *	TCA 27
	CT30 *	TCA 28
	CT31 *	TCA 29

b) The other instruments are shown on the flow diagram on page 26.

3.3.6 Control and Data display system.

a) The ASR control and data display system is based on a microprocessor which scans the 54 connected data channels every 173 msec, and at the same time executes the control system programme. The system is required to monitor process behaviour, to operate the ASR flow control, to provide visual and hardcopy display of process data as selected by the operator, and to control the system response to out of limit or emergency operational situations.

b) The flow control system, see the block diagram above incorporates three cascaded loops with the output of each acting as the set point for the loop inside it. The external loop is driven by the difference between the outlet temperature and the selected set point. The external loop is relatively slow as its main task is to maintain the selected output temperature during steady state operation.

The intermediate loop is much faster and is the primary means of transient control. The input signal is based on the temperature rise , sodium inlet and outlet temperatures. Outlet temperatures are measured on the back side of individual absorber tubes below the upper header. Inlet temperatures of the bottom headers of each panel are corrected by a time delay function to allow for the real flow situation up through the panels.

The result of the three inputs gives the inner controller a very rapid indication of the transient energy unbalance on the ASR which is insensitive to variations of flux map shape. The controller then determines the required flow rate as a set point for the inner loop.

The inner loop incorporates a feedforward signal derived from the sun presence sensor signal output by the Heliostat Field Control system. The signal is required simply to step up pump flow immediately insolation rises sharply from a low level i.e. as a cloud moves away from the sun. During the foreseen cloud transients flow rate will drop to the minimum (10%) and the temperature variations required by the intermediate loop for control will occur very slowly, far too slowly for the sudden response necessary as incident energy soars from virtually zero to maximum as a cloud is blown clear of the sun.

c) The Data Display uses a normal VDU/Keyboard to allow:

- Live data display of all measured and virtual data. The data can be displayed, six values at a time, on request in up to 14 operator defined measurement groups. The display can show up to 16 values as they are scanned and then starts to delete the earliest as the newest are entered.

- Display and modification of the temperature set point for control.

- Display and modification of the scale factor multiplying the sun presence signal.

- Display and acknowledgement of alarms related to digital inputs (physical or computed) and of alarms related to predefined analogue signal limits.

- Display and modification of alarms and protection limits assigned to measured signal inputs.

A printer is provided to allow hard copy production of the live data display, and the system configuration.

Additional features allow operator modification of:

- Data base and display

- Control Programme and display

- Control parameters and display

4 CONSTRUCTION AND INTEGRATION.

4.1 CONSTRUCTION.

4.1.1 Panel assemblies.

a) The panels were assembled in the following steps:

Tube inspection, cutting and bending.

Assemble "triplets" in fixture.

Fabricate headers.

Fabricate panel support structure.

Mount headers to structure.

Weld triplets to headers.

Regulate tube alignment. (By the adjustment of the stirrup supports).

Paint, cure and vitrify absorber surface.

Install ceramic and insulation.

The panels were then mounted together and the downcomer and connecting pipework fitted and the assembly packed as a unit for shipment.

b) The work illustrated by the photographs on pages 28 and 29, involved the solution of several manufacturing problems. The most vital was the welding of the tube supporting plates to form the triplets. Plasma jet manual welding was employed due to the very thin sections involved. It was found that the weld profile was very sensitive to parameter variations and considerable work was required to stabilise variables to obtain the desired profiles during production. A thorough programme of destructive testing of specimen welds was completed for the manually welded stirrup plates and for the tube/header connections.

c) The triplet connection to the header nozzles was done by an automatic orbital inert gas welding machine. (See photo).

d) In addition to stringent quality control of the materials mechanical, and chemical properties extensive welding quality control was performed. All welds were subjected to visual, dye penetrant and radiographic inspection. In addition the inside of the absorbers was examined by endoscope in the area of the welded stirrup plate supports.

The completed panels were pressure tested and leak tested with helium and the final assembly of the five panels was pressure and leak tested during the completion of manufacturing review.

4.1.2 ASR Site assembly.

a) The panel assembly was shipped to site together with all the materials to complete the ASR structural assembly. The door assembly and the electrical and control panels were the other items that were assembled and tested in Italy before shipment. The Spanish erection contractor arranged the local supply of ancilliary structures and platforms and the electrical contractor procured cable and its supporting materials locally.

b) The enclosing structure was erected on the ground and the panel assembly fitted into it. The structure was then lifted and bolted to the two main beams on the tower top. The original receiver was removed complete and the pipe support structure behind it was also removed intact to allow possible reuse. The aperture frame was assembled and then lifted in one piece, followed by the door assembly.

c) The vent and drain pipe systems including the new valves and supports were prefabricated and inspected in the factory as far as possible and were reinspected and constructed into two complete subassemblies on the ground to minimise the welding and testing required on the tower. All site welds of sodium tubes were done by factory personnel to the same standards as the factory work. Inspection was carried out by Bureau Veritas, Madrid.

4.1.3 Ancilliaries.

In addition to the main ASR structures and materials supplied from Italy the Spanish erection contractor supplied:

- Spacer supports to raise the Flux Measurement Apparatus 1250 mm.

- Additional platform to provide access around the new door frame.

- New supports to fix the front gangway to the main tower beam instead of the original receiver.

- A heat shield support to provide a screen of ceramic tiles in front of the front gangway.

- Supports for the spring hangers on the sodium piping behind the ASR structure.

4.2 INTEGRATION.

4.2.1. Pipework and Insulation.

a) Before removal of the original receiver the receiver loop was very carefully drained and filled with argon. The three sodium tubes (upcomer, downcomer, and vent) were cut outside the valves on the tower platform and the ends on both sides of the cuts closed with plastic caps. The caps on the original receiver were replaced with welded AISI 316 caps once the unit was on the ground. At all times an overpressure of argon was maintained in the sodium tubes on the tower, whenever possible from the inert gas system, and from a portable supply during the welding of the new pipes to the original ones. Plasma jet manual welding was used throughout. The same standard of work and quality control was maintained.

b) Once the three original tubes were connected to the new pipework and supports provided the upcomer was cut again, upstream of the platform valve, in order to insert the new drain connection tee, and the pipework was completed. Trace heating elements were fitted to the pipes and tested before the start of insulation work.

c) Preformed Mineral wool (Kaowool) insulation was used to the same standard as the original installation. The material is protected by stainless steel sheet instead of the galvanised steel used originally. All joints are silicone sealed against moisture.

4.2.2 Trace heating system.

a) In principle the ASR incorporated three loops of new elements delivered with individual controls to be connected separately to the original system. The new heating installation to be connected as follows:

Loop 1: total power 6 KW, comprising three parallel circuits heating the panel assembly. This loop was to be controlled by two thermostatic controllers sensing pipe wall temperatures in the loop.

Loop 1a: Three elements in series heating inlet pipe, panel 1 headers and downcomer, inlet pipe to panel 2. 53 m R 15S cable, 1797 W.

Loop 1b: Four elements in series heating outlet pipe, panel 5 headers and downcomer, inlet pipe to panel 3, panel 2 headers and downcomer. 67 m R14S cable, 2271 W.

Loop 1c: Four elements in series heating inlet panel 4, inlet panel 5, panel 4 headers and downcomer, panel 3 headers and downcomer. 53 m R 15S cable, 1779 W.

Loop 2: total power 2.5 KW, comprising one element of 97 m R 12S cable heating the entire vent system from the panel header connections to the original stop valve. The loop was to be controlled by a thermostat.

Loop 3: total power 1.2 KW, comprising one element of 44 m R17S cable heating the four drain connections, valves and the connection pipe to the upcomer. The loop also incorporated a thermostat for control.

b) The cables were specified to be the same mineral insulated heating cables as the original installation. The same construction of cold ends, and connection sleeves was desired and the quality assurance procedure was to be identical. This procedure included a test that applied 1.5 KV alternating at 50 Hz to the assembled heaters within 8 hours of the cable being taken from a bath of water after immersion for 12 hours. Ten other tests were also done including radiography, bending, heating and detailed measurements.

c) During final manufacture it was found that the controller of the original trace heating system had three spare channels available. The thermostats supplied with the ASR were not therefore connected. Three additional thermocouples were installed to implement the three spare channels available in the original controller to monitor and control the three new ASR heating loops.

d) Considerable difficulty was caused by the heating elements fitted to the original pipes that were removed with the original receiver. These elements spanned the interface areas and could not be cut with the pipes as they continued down the tower for a considerable distance heating pipework that was not to be disturbed.

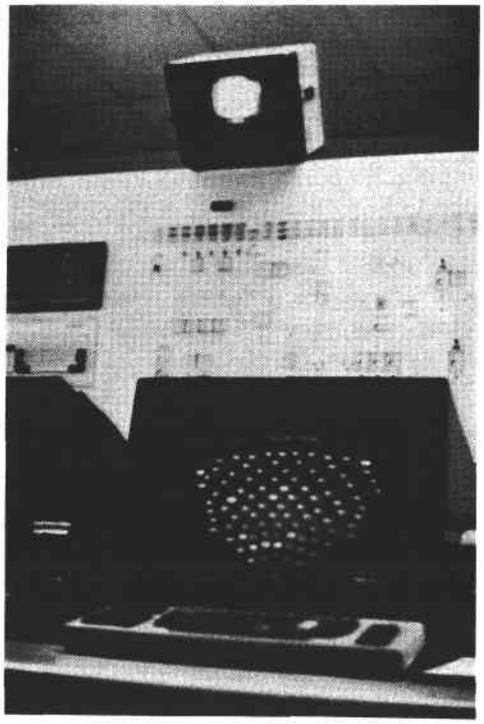
The element on the upcomer/inlet pipe was successfully removed from the superseded pipe and reinstalled on the new pipe to partially supplement the new element.

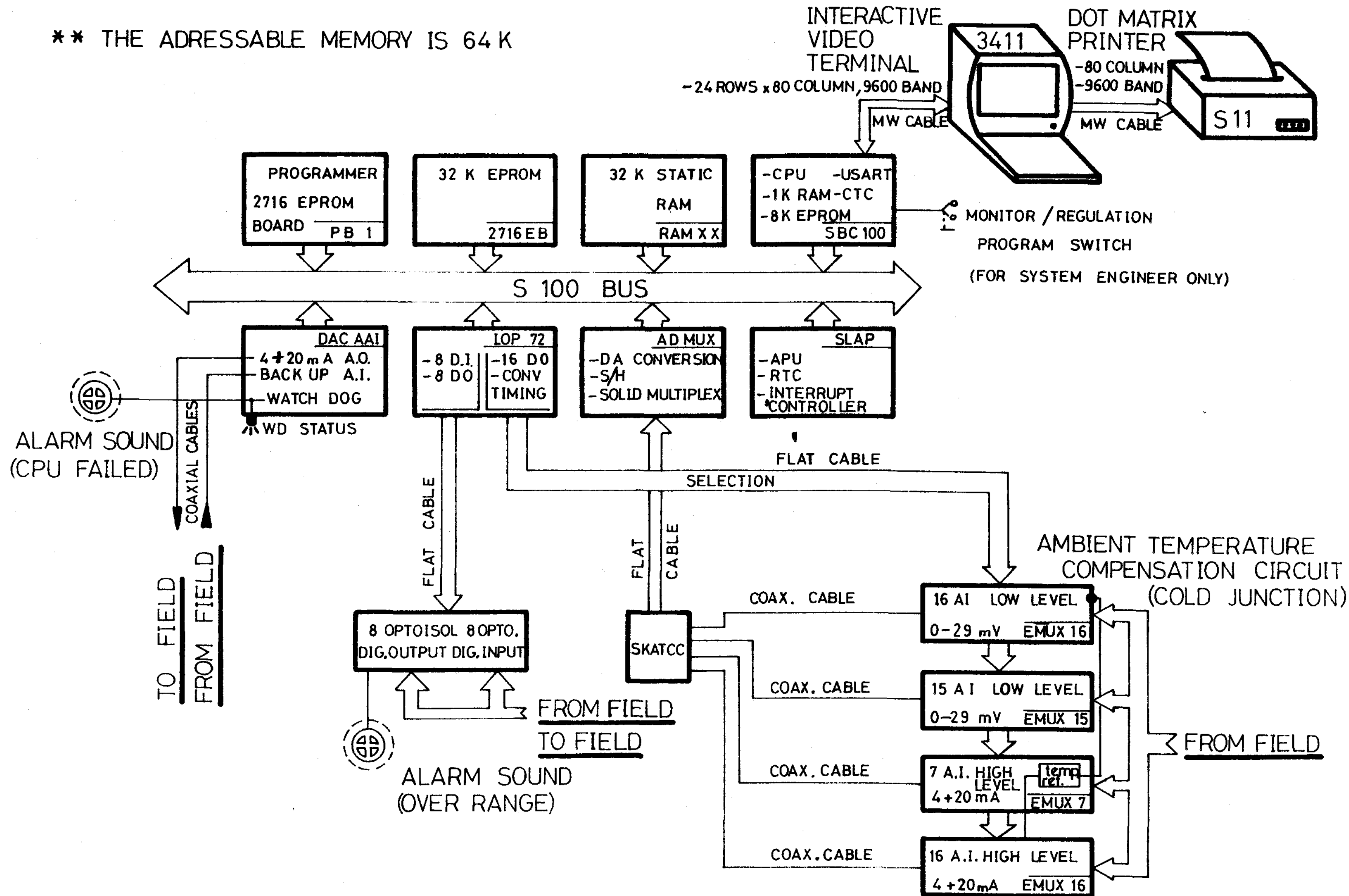
The element on the overflow/vent was broken during dismantling. A new cold end was fitted in situ to the undisturbed part but as the effective length had been reduced from 17 m to 8.3 m a reduced supply voltage was required to maintain the original current. This was arranged by the addition of a special transformer to the power supply for this element in the original power supply cubicle.

The element on the downcomer was much more delicate than the others, due to its life at higher temperatures, and it broke in several places during removal from the superseded tube. An in situ repair was attempted but repeated attempts were unsuccessful. The eventual solution was to remove the insulation from the pipe down the tower to the beginning of the element and to replace the original element with a 50 m long element of the same power rating that was available from the spares for the original plant.

4.2.3 Control and data display system.

a) The system installed is illustrated by the figures on pages 38 and 39. The entire interfacing and data processing facilities are built into a rack which is installed in the CRS Marshalling Kiosk beside the original cubicle CV01 GJ04. The interactive video terminal is fitted into the CRS control board in the control room beside the receiver instruments. The printer is mounted in the back of the board, behind the terminal. The ASR control station is illustrated below with a view of the control desk and panel modifications.



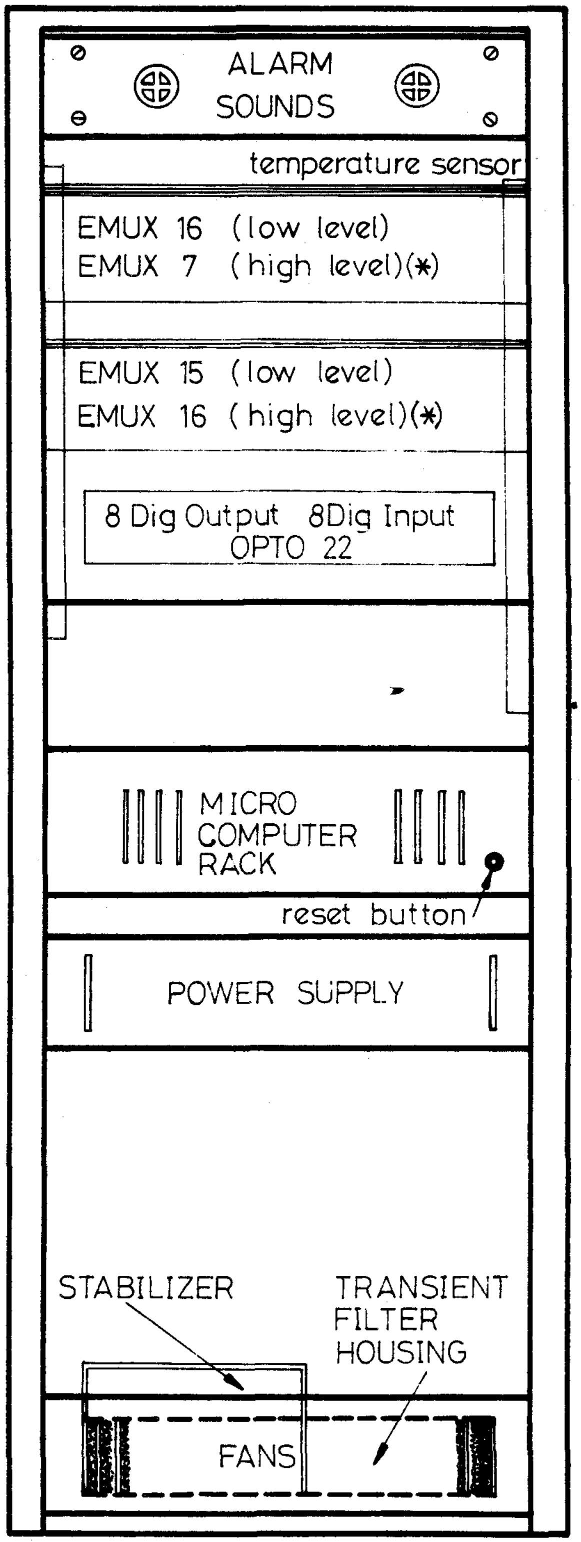


DWG (1)-GENERAL CONFIGURATION

STUDIO DI INFORMATICA
s.d.i.
MILANO

MICROPROCESSOR CONTROL SYSTEM FOR THE ADVANCED SODIUM RECEIVER OF ALMERIA SOLAR PLANT.

s.d.i. STUDIO DI INFORMATICA MILANO	MICROPROCESSOR CONTROL SYSTEM FOR THE ADVANCED SODIUM RECEIVER OF ALMERIA SOLAR PLANT.



DWG ② RACK LAYOUT (FRONT VIEW)

b) The rack contains:
- Power filtering and stabilising
- Microprocessor (32K Eprom, 32K RAM, Z80 CPU, S 100 bus)
- 4 EMUX cards (16 input elements each)
- 16 input/output optically isolated modules
- EPROM programmer
- Internal compensation box

4.2.4 Instrumentation.

a) As previously mentioned 19 temperature sensors were disconnected from the original receiver. They were disconnected from their compensation box at the top of the tower. 18 of the ASR sensors as listed on page 31 were reconnected to this box so that they became integrated into the original DAS system. A current signal was supplied to the ASR microprocessor from each one by extending the original current loop from the original transducer in the marshalling kiosk to the original DAS.

b) The remaining new temperature sensors were connected to two new boxes on the tower and then to the marshalling kiosk where the uncompensated signals are led directly to the microprocessor. Details of all the sensors fitted are listed in the tables on page 31.

4.2.5 Power Distribution.

The ASR is installed as a new component of the CRS system with each consumer supplied from the relevant sub-supply as follows:
- Trace heating power relay panel CP-1 from BN01 GJ04
- Doors Mechanism from BT02 GJ02
- Valve control panel LP-1 from BT01 GJ01
- Control and data system from UPS.

4.2.6 Ancilliaries.

a) Flux measurement systems. Both the FAS and HFD systems were replaced as they were removed. The assembly was refitted on top of extension pieces that effectively raised the level of the original mounting plates by 1250 mm. Minor damages to the apparatus were rectified.

b) Lightning conductor, CCTV, Air warning lamp. These items were fitted tothe top of the ASR structure before the completion of installation. The lightning conductor was extended 4 m to clear the new CCTV camera and was reconnected to the tower structure.

5 TESTS AND TRIALS.

5.1 SUBSYSTEM FUNCTION AND PERFORMANCE.

Upon completion of the installation of the ASR an agreed programme of testing began. The complete programme, as used, is TR 15 Rev. 2 Dec. 1983, in the final documentation. The tests were conducted in the sequence described and the successful conclusion of each one was a prerequisite to the start of the next.

5.1.1 Control and Data display.

a) The first activity involved the start up and testing of the control microprocessor. After loading the operating programmes the system was started to allow testing and to allow a start of operator training. This was particularly important as the whole test programme depended upon considerable support from the operators of the existing plant.

b) The tests involved the input of simulated signals and the measurement of the output responses. The procedure verified the installation and function of the system (scanning, connection, data display and printing, signal conversion, etc.)

5.1.2 Trace Heating System.

a) With the ASR installation complete, the pipework full of argon, the electrical system operating and checked, and provisional documentation of the installation available, the three new loops and the three original loops that had been disturbed were tested.

b) Once steady state had been established the power consumption, and the temperatures achieved relative to the selected set point were recorded. Temperatures were measured from the data systems, by direct measurement with a contact thermometer, and by adjusting the setpoints of the control thermostats, installed but not used, to observe when they switched.

c) The alarm threshold values were then checked, on the original controller.

5.1.3 Sodium and Cover Gas Valves.

a) With the trace heating still on, the operation of the four new drain valves and the five vent valves was verified.

b) The valves were first opened and closed three times by hand, one by one. This verified the endswitch operation and the status annunciators. The two groups were then opened and closed three times from the control panel, first individually and then simultaneously to simulate the response to an emergency drain.

5.1.4 Doors.

The doors were opened and closed several times with the hand cranks and the remote controls. The times of travel were checked, correct status indication checked and the correct positioning, open and closed, visually inspected.

5.1.5 Instrumentation.

a) The functioning of the reinstalled flux measurement systems was checked but performance could not be checked before operation. Similarly the reinstalled instruments in the sodium pipes were checked for function.

b) With the trace heating still on, the function of all the temperature sensors was checked. First the installation (continuity, polarity, insulation, connectors and identity) and then for the correct data on the DAS, the microprocessor and the panel instruments relative to spot measurements with a portable sensor.

5.1.6 Interlocking Systems.

a) All the emergency switches on the tower were tested including:

- door controls
- sodium leak sensors
- manual trips
- hall door trip

b) All the signals that initiate a receiver alarm or trip were then simulated to verify the control system response, followed by the interlocks between the receiver and the heliostat field. These tests verified the ability of the microprocessor to quickly defocus the heliostat field and increase the sodium flow when an overtemperature situation is detected. They also tested that the original system interlocks were responding correctly to emergency signals from the alarm inputs on the tower.

5.2 PREHEATING TESTS.

5.2.1 Heliostat Aiming.

With no work in progress on the tower the aiming and images of all the heliostats could be checked. The coordinate revisions related to the new aiming strategy were first entered and then each heliostat tracked on the absorber in turn. The images were monitored using the CCTV and were adjusted until all were agreed to be satisfactory.

5.2.2 Preheating.

Following the original plan it was then attempted to preheat the ASR using heliostats 19,65,22,39 aimed at B2,B1 and A respectively. Several interruptions followed by pauses with the doors closed failed to produce a satisfactory temperature distribution on the absorber. An ad hoc experimentation eventually produced an apparently satisfactory solution with four heliostats from the intermediate rows aimed at the corners of the absorber and from two to five aiming intermittently at the three central aim points.

The acceptable temperature distribution over the absorber, aperture frame and door supports was verified and then maintained while the ASR was filled with sodium and sodium circulation begun from the cold storage tank.

5.3 FUNCTIONAL TESTS WITH SODIUM.

a) The function of the following systems was then tested again:

- Instrumentation
- Drain and Vent Valves
- Trace Heating System
- Emergency Switches and Interlocks

b) In addition the function of the sodium pressure sensor, level indicator, flow meter, pump speed indicator,the vent valve, and the flux measurement systems from the original system were checked.

c) The retest of the new valves was done with the pump off and isolated. One of the vent valves was found to be leaking but the fault was removed by adjusting the endswitch to allow the valve to close fully.

The trace heating system was then retested satisfactorily before the pump was restarted. Sodium circulation of the heated ASR was then restarted in preparation for testing with solar power input.

5.4 RECEIVER INTEGRATION.

After a short period of initial operation (24 hrs) at low power levels before the start of serious testing the ASR was shut down and drained to allow a number of minor finishing works on the tower (as required by the Plant Safety Rules for working on the tower). During the restart an incident occured which resulted in the ASR being shut down and repaired causing a long interruption of the test programme. The incident and its consequences are discussed below.

The integration phase was intended to prove the function of the integrated ASR by careful operation at increasing power levels from start up to a steady load and then shut down. Integration would be completed by the demonstration of a full day of normal operation up to the nominal power, provided the weather remained clear. Transient and emergency operation would be in the scope of later tests. Henceforward the Absorber surface would be visually inspected at the end of each test day to check for any new deformations.

5.4.1 Stage 1 - 50% Power.

a) Target operating level: 425°C sodium outlet temperature, 1.5 MW thermal input power (48 Heliostats at design insolation), approx. 1.2 MW thermal output.

b) The test procedure required starting with the doors closed, an initial flow of 10 m^3/h recirculating to the cold storage, and the outlet temperature set point at 425°C. The Heliostats to be used would be set according to the standard ASR 3 point aiming strategy.

The doors were then to be opened and the heliostats focussed, row by row, balancing the aiming position, with a pause of one to two minutes between each increment. When the temperature reached the set point the control was to be switched to automatic. Power increments should continue until the desired level was achieved, as indicated by the thermal output derived by the DAS.

The system should then be left to run for at least half an hour without adjustment provided the sky stayed clear to observe the control behaviour. The test was to be concluded by defocussing heliostats row by row over 10 - 15 minutes. Flow should have been reduced automatically as the input power dropped, maintaining temperature, down to the minimum. At minimum flow the set point was to have been lowered and the system switched to manual. With all the field defocussed the doors could be closed and the receiver would slowly cool to the inlet temperature.

c) Minimum data required: all ASR temperatures, flow, pressure in receiver, sun presence signal, pump speed and power, direct insolation, heliostat status.

Evaluation would consider:
- Steady state temperature profile of the tubes.
- Transient heating and cooling characteristics.
- Temperature distribution on panels.
- Power distribution on panels.
- Temperature distribution on aperture frame.

d) The test was run according to plan on 13.11.83 from 11.56 hours to 14.58 hours. Insolation was poor starting at 700 W/m and declining steadily. 67 Heliostats were needed to reach the desired power level. A flux measurement at 14.17 hours showed :

- Insolation 662 W/m^2
- Total power 1260 KW
- Average flux 52 KW/m^2
- Peak flux 461 KW/m^2 (HFD reading)

The test was stopped after 3 hours due to the risk of cloud passages.

5.4.2 Stage 2 - 75% Power.

a) Target Operation. At least half an hour steady operation at 500°C outlet with 2.2 MW input power (70 Heliostats at 920 W/m^2), 2.0 MW thermal output. This test to be followed by a whole day of similar operation. The outlet temperature would then be raised to 530°C for another short test at this power level.

b) The procedure was exactly the same as for the earlier test except that the flow was not to be allowed to exceed the maximum of 30 m^3/h during the whole day test.

c) The tests were carried out as planned from 17.11.83 to 30.11.83 except that the power levels were gradually stepped up to 100%.

5.4.3 Stage 3 - Nominal power.

a) Target operation. Outlet temperature set to 530°C, full power operation (all heliostats in use).

b) The procedure required a normal warm start followed by the sequential focussing of heliostats as before until all were in use. Steady state operation should then be maintained for as long as possible followed by a shut down as before. Sky conditions should be cloudless and operation confined to within 09.00 hours to 18.00 hours to avoid severe image distortion.

c) The test was conducted as planned on 01.12.83.

5.4.4 Conclusion.

Evaluation showed a sufficient agreement between the computed and actual results. The control system had been proved to work well automatically throughout and the operation had been effective. Operation had recorded a peak flux of 1020 KW/m , and a delivered thermal power of 2.4 MW at an insolation of 882 W/m .

5.5 FUNCTIONAL TESTS AT NOMINAL POWER.

5.5.1 Instrumentation.

with the ASR in operation at steady state at full power and 530 C outlet temperature the temperature measurements were checked again on 08.12.83. Visual and printed displays were validated and checked with the DAS records where possible.

5.5.6 Doors.

Upon conclusion of the instrument check the field was defocussed and the doors closed and opened twice to check their function on a hot receiver. The travel times were recorded and the temperatures sensed on the doors.

The fit of the doors had been adjusted during the previous works on the tower and this test verified that the work had been effective.

5.6 CONTROL AND OPERATIONAL TESTING.

5.6.1 Cloud transient simulation.

a) The objective was to verify the safe response of the system to a range of artificially induced transients when working at or near the design point.

b) The procedure involved the rapid defocussing of different numbers of heliostats when operating at a high power level, at steady state, with all heliostats in focus. The heliostats would then be rapidly refocussed either after an interval or immediately dependent on the type of transient simulated (V or U). For the more severe transients it was necessary to manually regulate a simulated sun presence signal but otherwise full automatic operation was required. A cloud free sky was essential to avoid disturbance of the planned disturbances.

c) The simulations were as follows:

- 25% U Transient. Defocus 23 heliostats in 5 - 10 seconds. Wait until steady state conditions are reestablished at the reduced power level. Refocus the heliostats standing by within 5 - 10 seconds.

- 50% U Transient. Repeat with 44 heliostats. Time for heliostat de-and re-focussing 10 - 15 seconds.

-50% V Transient. Defocus 44 in 10 - 15 seconds and refocus after not more than 30 seconds. Sun signal modification required.

- 100% V Transient. Defocus all with the same procedure.

- 50% U Transient with sun signal manipulation. This test was run as a rehersal for the last where the manual manipulation of the sun signal was crucial to the safety of the ASR.

- 100% U Transient. Defocus all in less then 30 seconds. Wait with the doors open and minimum flow held automatically until outlet temperature equals inlet then refocus all in less than 30 seconds. Sun signal manipulation crucial. During the wait flow would transfer automatically to return to the cold storage as the outlet cooled. During the repowering flow would return to the hot tank.

d) Evaluation of each test demanded a satisfactory comparison with the simulated computer predictions and the control parameters were adjusted throughout to perfect the results.

5.6.2 Operation from cold start up.

a) This test was planned to verify the entire procedure described in the Operating Manual for a cold start of the empty receiver through preheating, filling, and power increase from zero to full. The objective was to verify that the system was ready for normal operation.

b) This plan was changed due to the circumstances following the incident that had disrupted the early testing. One of the main results of the delay was the development of a new preheating and filling procedure by the plant operators and the Italian partners. The new procedure was finally tested and accepted on 10.11.83 (test result 3.3.4/3 in the final documentation).

c) With the preheating and filling just completed the remainder of the cold start procedure is identical to a warm start. In view of the special attention already given to the new procedure it was considered an unnecessary delay to the test programme to drain and cool the ASR to conduct the planned test in the planned sequence.

5.6.3 Operation from warm start.

This test was planned to confirm the operablity of the integrated ASR in terms of the normal, every day, start up. With the backwall still warm (around 300°C) the doors can be opened and the heliostats brought into focus at about one row per minute. The test was to be conducted by the operators strictly according to the operating manual.

The test was officially conducted as planned on 10.12.83 but the procedure, in fact, was already in every day use from the beginning of the month.

5.6.4 Operation to normal shut down.

As with the normal start up this test was already in every day use according to the specified procedure before it was formally conducted on 08.12.83.

5.6.5 Quick shut down during normal operation.

This test involved the simulation of an interlock command that would defocus all the heliostats on a single command to protect the ASR from an overtemperature alarm or an external system failure. The system was required to be working at a high load at the start of the test. The test was conducted according to plan on 01.12.83.

5.6.6 Other Tests.

a) An evaluation of the pressure losses between the inlet valve AA04 and the outlet pressure sensor CP03 has been included in the test results. The analysis indicates a drop of 0.75 bar through the ASR at 28.6 m^3/h flow, 267°C inlet, 527°C outlet.

b) An additional functional test report is included for a test on 30.11.83 of the trace heating elements installed on the ASR drain system. These elements were installed to replace the original which failed in November due to installation defects.

5.6.7 During the two months of testing from the completion of the repair until acceptance the ASR operated for 129 hours and absorbed 155.917 MWh thermal energy. Acceptance was agreed on 15.12.84 upon the completion of the above tests.

5.7 INITIAL OPERATION

5.7.1 Evaluation testing.

a) Losses evaluation. Thermal losses from the ASR have been evaluated both by measuring the difference between incident and absorbed energy during operation and by measuring energy lost from sodium circulated during non operation. The non operational tests included circulation during the day with doors open and closed and overnight at differing flow rates. The tests included a reverse flow test.

b) Reverse flow test. By using differential argon pressure with the pump shut down it was possible to reverse the normal flow direction. Hot sodium was introduced at about the mean of the operating inlet/outlet temperatures and the temperature losses observed at two flow rates (6 and 12 m^3/h). Sufficient data is now available to quantify the steady state thermal performance of the ASR and the work is described in the paper by Jacobs/Selvage.

c) Pressure loss verification. After the recallibration of the CRS instruments in February the pressure loss evaluation was repeated more thoroughly.

d) Transient performance. In addition to the observation of numerous real cloud transients in 1984 the time constant and the gain of the ASR have been measured. With the ASR operating in steady state at design temperatures the flow control has been switched to manual and the flow rate stepped up about 10%. The resultant response of the ASR temperatures as they fell to a new steady state was observed before repeating the transient by returning to the normal setting. The comparison of the results with computer model simulations at 8, 20 and 30 m^3/h flow rates shows a very close agreement with the predicted characteristics upon which the control system design is based.

5.7.2 Routine Operation.

The ASR has been operated on a routine basis since Acceptance except for a short shut down and draining in April to perform final finishing works on the tower and to complete the improvements decided upon after the September 1983 filling incident. The activity is summarised in the table on page 50.

MONTH	Operating Days full	Operating Days part	Hours non	MWh in focus	HFD absorbed	meas-ures
Jan	11	15	5	56.11	80,578	9
Feb	7	12	10	70.18	100,750	10
March	8	14	9	97.47	119,947	0
April	5	6	19	24.25	5,355	0
May	1	17	13	53.22	27,087	0
June	0	19	11	129.51	133,618	30

5.7.3 Special Activities.

The Operators, the Italian Partners and various equipment suppliers have worked together to resolve several development problems.

a) The response of the sodium pump controller was modified in January to speed up the rate of acceleration without introducing excessive hunting under steady flow conditions.

b) Work began in January on the restoration of a revised sun presence signal from the HAC, to be used by the ASR control system. At present the signal has been improved to allow for the effect of sun angle but a way of reducing the effect of global radiation is still under development.

c) The DFVLR has organised a complete re callibration exercise of the CRS instruments. In addition the HFD was modified to suit the configuration of the ASR.

d) Improved thermocouples have been fitted at the inlet and outlet.

e) A further trace heating failure was discovered during the April shut down and this was repaired in situ.

f) Considerable effort has been devoted to the improvement of the heliostat aimings due to the improved image quality demanded by the ASR. A software error concerning the plant latitude was corrected and a lot of work was done on individual facet alignment.

6 EXPERIENCES AND CONCLUSIONS.

6.1 PERFORMANCES.

A simulation procedure was established to assess the data from the Data Acquisition System and the Heat Flux Distribution bar. An experimental data set composed of measurements from HFD (incident flux map on December 23, 1983, 12:10 solar time and DAS (ASR temperatures and flow rates) has been considered and compared with data computed with HELIOS and THERESA. (As is well known, the two computer codes are able to compute the image of a heliostat field and the temperature distribution in billboard sodium cooled receiver, respectively).

A centered peak flux of 989 kW/m is obtained with 940 W/m of incident insolation. The total power collected on the HFD scanner area (5 x 4.2 m) is 2448 kW (the integration was performed on the HP-85). The DAS estimate of the power reflected toward the target at the same instant is 2682 kW. In order to perform a better analysis, the same HFD flux distribution was integrated with a more sophisticated program (SPLINEB) implemented in April on the site VAX computer. The figures for total power, computed with three different integration methods are:

- 2574 kW (integration after a spline interpolation)

- 2616 kW (integration with the Simpson formula)

- 2612 kW (integration with the Albrecht formula)

It was assumed that 2600 kW was the most reasonable indication of the real power incident on the HFD plane, and the HELIOS program was used to reproduce this figure. At the same time (December 23, 1983, noon) the flux distribution reflected by the 93 heliostats was computed with the code input parameters at the values used during the ASR design computations, with the exception of the value for direct insolation and mirror reflectivity. For insolation the measured value of 940 K/m was used. The reflectivity was parametrized in order to reproduce the 2600 kW reflected power. With mirror reflectivity at 80% (very close to the estimate from spot reflectivity measurements) the program calculated 2603 kW on the target (HFD plane - 75 cm. behind the ASR tube plane; centre at 44 m.). The computed flux distribution has a peak value of 1020 kW/m , very close to the experimental one (989 kW/m).

As the agreement between measured and computed data is good, the HELIOS program was applied again in order to compute, in the same condition, the flux distribution on the receiver tube plane.

The result of this computation on a 3 x 3 m. target is 2586 kW reached the target, with a peak flux of 1230 kW/m . This flux map is assumed to give the real power distribution incident on the receiver tubes at that time: it is used as the input data for the thermal analysis of the receiver performed with the THERESA program. The results of these computations are compared with measurements recorded by DAS and stored on tape. They show that at 13:05 (local time) the receiver was operating at a flow rate of 30.58 m^3/h (7.6 kg/sec with a sodium density of 855 Kg/m^3) with inlet and outlet temperatures of 265 and 529.6°C, respectively. From a steady state thermal balance evaluation, about 2500 kW seem to enter the fluid (the DAS value reported on the HFD measurements is 2538 kW). However, this figure must be modified in order to take into account an error in the flow rate measurement. Preliminary results after the flow meter calibration suggested that these measurements should be reduced by about 10% in order to approach the true value. For this reason, for the computations, the inlet flow rate was reduced from 7.6 to 7.0 Kg/sec.

Temperatures in the receiver tubes, headers and ceramic backwall were computed. The input data include, in addition to the incident flux distribution, inlet temperature and flow rate, as well as heat transfer correlations and ASR geometrical and physical characteristics. First the power incident on the 2.75 x 2.85 m. billboard receiver is computed, establishing how this power is divided between the 5 panels. Then the incident power distribution on 15 receiver tubes is computed, and the thermal balance equations in the fluid, tube wall, and backwall are solved. The code output presents: 2560 kW impinge on the receiver and 2220 kW enter the sodium with an overall efficiency of 88.6%. Fluid temperature increases from 265 C to 529 C (receiver outlet).

Panel number 3 (quite high incident flux and reduced temperatures) shows the highest efficiency (91.7%). Panel number 2 shows the lowest one (83.3%). Panel number 5 presents the largest losses (96 kW), while Panel number 1 shows the smallest (26.5 kW).

6.2 FAILURES.

6.2.1 General.

The ASR assembly supplied from Italy has worked well except for the failure of three temperature sensors to date. The serious failures have all been related to the trace heating system integration work performed on site.

6.2.2 Trace Heating. Failures have occured due to following causes:

- Incorrect installation. On the drain system the new element was wrapped around the valves too sharply and without protection from chafing against the valve bodies during thermal cycling. The element outer cover cracked at the bends and the ingress of humidity destroyed the whole element.

- Ineffective in situ connections. Several failures have ocurred where a connection of a cold end to a shortened heater was attempted. So far connections to "cool" heaters on the inlet piping have remained intact but connecting the hot elements has proved impossible.

- Disturbance of unmodified elements by adjacent interface work. Although the evidence cannot be conclusive the most critical failure occured in an element that was not to be affected by the ASR installation. The element failed at the connection box it shared with an element that was modified after the connection box had been removed and replaced.

6.2.3 Filling Incident, September 1983. Full details of this incident are listed in the references.

a) The ASR was prepared for filling for the second time on 7th September. After preheating the valves were opened to allow sodium to rise into the receiver. A failure of a trace heating element in the downcomer was not observed and this line plugged with cold sodium preventing the entry of sodium into the drain line to fill panels 2,3,4,5 from the bottom.

b) Only the first panel could fill from below from the inlet/upcomer. Anomalous flows and temperatures were observed in the headers, absorber and vent line as sodium filled the remaining panels both by the normal flow piping and by overflow through the vent system.

c) When the plug position was identified an emergency circulation was established by using the vent of the fifth panel as an outlet. The plug eventually melted and normal circulation resumed until the ASR was again shut down for a thorough technical investigation.

d) Unacceptable distortion was found to have occured in seven tubes in panels 2,3 and 4 but panels 1 and 5 were undamaged.

e) The incident had also exposed the difficulties of not all the temperature sensors being connected to the DAS and the desirability of individual control of the vent valves.

6.3 REMEDIAL ACTIVITIES.

6.3.1 Absorber Distortion.

Franco Tosi conducted an extensive investigation in Legnano for the DFVLR in order to:

- Explain the observed distortions by theoretical analysis and to reproduce the phenomenae by laboratory experiments.

- Propose a repair procedure that would fully restore the effectiveness of the ASR.

- Propose procedural improvements to prevent a recurrence.

The work was done effectively. The distortions were agreed to be due to the uneven filling of preheated tubes in individual triplets such as would occur if sodium entered first by the upper headers. An in situ repair procedure was developed and a team subsequently came to site and straightened the distorted tubes.

6.3.2 System Improvements.

a) The trace heating system was thoroughly checked and the monitoring and alarm system restored to full function.

b) It was decided to connect all the ASR temperature sensors to the DAS system and the necessary 20 transmitters were ordered. These were fitted in April 1984.

c) It was agreed to reconnect the vent valve controls so that the valves could be controlled individually from the control room. A system was designed by the POA and installed in April 1984. The system allows the panels to be vented individually provided that the ASR doors are closed and the plant out of operation. This has proved extremely useful for daily venting and would allow better control during filling in the event of further difficulties.

d) The main activity on site was the development and testing of preheating and filling procedures. Considerable work has been done to ensure an optimum temperature distribution before filling; to ensure the controlled and even rise of sodium in the tubes and to ensure that no argon is trapped. The subsequent fillings in November and April 1984 demonstrated continuing improvements but the topic is not yet closed.

6.4 CONCLUSIONS

6.4.1 General

a) The ASR has already fully demonstrated the feasibility of high flux sodium cooled receivers. Its thermal performance exceeds expectations and operation presents no major difficulties in spite of the fact that the ASR has been fitted into a plant designed around a very different receiver.

b) The soundness of the conceptual design has been proved. With hindsight it now seems that all the effort devoted to investigating the design has not been necessary. All the analyses carried out from 1980 to 1983 are very impressive but the ASR design was only validated, not changed. With the cavity receiver always available for substitution; it is now clear that the ASR could have performed equally well in 1982 at minimum risk to the SSPS project.

c) The improvement in performance over the original cavity receiver is very large. Even accounting for the improvements in the understanding of CRS technology that occured between the two designs there seems to be little attraction in pursuing the study of sodium cooled cavity receivers.

d) The ASR continues to demonstrate many lessons that must be learned and details that must be improved before the concept is expanded for use in larger solar power plants. It is particularly important that the apparent complexity of the ASR due to the small scale of the installation is not upscaled. The benefits of high flux rating in terms of compactness have not been realised at the SSPS due to the considerable infrastructure of pipe supports, header pipes, instrumentation and auxiliary systems.

6.4.2 Tube coating. The simple application of Pyromark to the absorber surface is out of tune with the level of technology applied elsewhere, especially as it concerns the key performance parameter - absorbtivity. The coating originally applied had deteriorated perceptibly after the 24 hours of operation to the filling incident and was touched up after the repairs. Considerable deterioration has certainly occured since. The availability of advanced absorber coatings must be improved.

6.4.3 Tube configuration.

a) Panel layout. The flow pattern of the ASR has proved extremely effective both in terms of minimising losses and in terms of giving a very fast control response. The relative complexity of the downcomer, header and connection piping behind the absorber necessary to connect the panels demands high costs for the piping, insulation and supports and increased risks and costs from the extensive trace heating.

b) Triplets. The triplet configuration has been proved to work as hoped for. However the distortions from the filling incident were a result of uneven filling of different tubes in some triplets. This was probably due to the fact that each tube of each triplet is connected at a different level to the headers. When the headers were improperly filled and some triplets were filled from above the tubes were not filled simultaneously. The problem could be avoided if only identical tubes were welded together or if the stirrup supports were avoided.

c) Drain pipe. The drain connections to panels 2,3,4,5 are rather small for even filling as shown by the report on the April filling. The first panel can fill significantly faster directly from the 80 mm dia. upcomer than the others through the 50 and 25 mm drain pipes.

6.4.4 Trace Heating and Instruments.

a) There are many vital instruments and trace heating elements installed in the ASR body behind the absorber. To replace almost any of these is impossible without considerable disassembly. Failures of thermocouples have already occured. A commercial design would need the provision of redundant spares or means for easy replacement, or both.

b) The installed trace heating power is too low for reliable filling. During the April filling it proved impossible to heat the drain piping to the desired temperatures. Sodium temperatures as low as 141 C were observed in the drain lines even though the inlet was up to 240 C.

c) The ASR installation repeatedly emphasised the care necessary to install trace heating elements successfully, the unreliability of in situ repairs, the difficulties of repair by replacement and the crucial importance of trace heating system performance.

6.4.5 Sodium circulation.

a) The entrapment of Argon has proved much more significant than expected. Venting is now performed at least every day to prevent the build up of gas pockets in the upper headers. The situation is aggravated by the lack of adequate sodium level indication at the top of the receiver.

b) The eventuality of a pump seizure or blockage suddenly stopping the flow of sodium will damage the ASR if working at high power. The sodium circuit will remain intact but unacceptable distortions of the absorber are probable. Future designs should provide for pump redundancy or some form of header tank to ensure continuity of flow until a "dive" is executed under all circumstances.

6.4.6 Heliostat Field Control.

The increased demands of the ASR on image quality and the severity of the possible transients are highlighting deficiencies in the existing system. Improvements will be necessary in the system software to operate future advanced receivers. The inability to refine individual aiming points quickly during operation and the time taken to regain control after a power failure is particularly worrying.

6.4.7 Closed Circuit Television (CCTV).

The fortunate coincidence of the completion of the CCTV installation with the installation of the ASR has proved vital to the sucessful operation of the ASR. It would be impossible to operate safely with the existing HAC without the ability to see the image on the absorber on TV in the control room.

6.4.8 Preheating and Filling.

a) The question of how best to integrate an ASR in a future plant remains unresolved concerning preheating and filling. Preheating and filling has proved much more difficult than expected to do quickly. The provision of doors allows acceptable losses if circulation is maintained overnight to avoid daily filling, but their use in larger installations will be difficult. If the ASR were not fitted with doors the time lost every day during preheating and filling would be unacceptable and the overnight losses without draining equally severe.

b) Boosting the trace heating power installed would certainly help and more investigation is required of feasible heating procedures with heliostats but design changes are also likely to prove desirable.

6.4.9 Insulation, Aperture and Doors.

a) The ceramic backwall has worked well. The leakage of flux between the absorbers is probably lower than anticipated during normal operation but the peak values possible after distortions such as occured during September 1983 fully justify the conservative installation.

b) The limits of allowable temperatures on the aperture are considerably reducing operational effectiveness. Every clear morning and evening partial field operation is necessary to limit spillage on to the aperture frame, even though the field is tracking accurately. Indication that the current limits are conservative is given by the sucessful resistance of temperatures up to 420°C that occured after a power failure. Future designs will require more attention to the minimising of the aperture structure and to increasing its resistance to high temperatures as the tracking accuracy of the SSPS CRS field will not be easily improved with larger heliostats and fields.

c) The doors provided work well and are essential to minimise losses. However the use of such large structures on larger receivers is doubtful. No difficulties have yet been experienced with overtemperatures even though the doors are often exposed to high fluxes during power failures and the time consuming reacquisition of the heliostat field.

6.4.10 Organisation.

The Installation of the ASR into an existing plant by a national group new to the site was no easy task. Mr. Carlo Sala of Agip deserves high praise for his control of the installation work. The interest and enthusiasm of the POA allowed Dr. Di Benedetti to establish a working relationship with the Plant Operators very early in the commissioning which has since proved invaluable to the solution of operational problems and the organisation of effective evaluation.

7 FINAL DOCUMENTATION AND LITERATURE

7.1 Conceptual Phase

a) SSPS Stage 2 Implementing Agreement.

b) Progress Report No.1 "Second Sodium Cooled Almeria Receiver" by: ANSALDO, ENEL, FRANCO-TOSI, SNAMPROGETTI. (October 1979)

c) Progress Report No.2 "ASR for Almeria" by: ANSALDO, ENEL, FRANCO-TOSI, SNAMPROGETTI.(April 1980)

d) Progress Report No.3 "Baseline Configuration of 2.7 Thermal MW ASR for Almeria IEA-CRS" by: ANSALDO, ENEL, FRANCO-TOSI, SNAMPROGETTI. (May 1980)

e) Progress Report No.4 "Baseline Configuration of 4.2 Thermal MW ASR for Almeria IEACRS" by: ANSALDO, ENEL, FRANCO-TOSI, SNAMPROGETTI. (May 1980)

f) CRTF Experiment Application by: Luciano Cinel. (Oct. 1980)

7.2 Contracts.

a) Contract 387/4013/79 "Provision of an Advanced Sodium-Cooled Receiver to the SSPS CRS 500KWe Solar Power Plant" between DFVLR-Italian Partners.

b) Contract Change No. 1 to Contract No. 387/4013/79.

c) Contract 387/4012/80 "Engineering and Surveyance Support in connection with contract 387/4013/79" between DFVLR-Interatom.

d) Contract 37801/4024/81 "Advisory and surveying support in connection with the ASR Receiver" between DFVLR-Dasag Engineering.

7.3 Design and Construction.

a) SSPS Technical Report 3/83 (2 vols) "ASR Topic Reports prepared by the Cotracting Companies, Agip Nucleare, Franco Tosi Industriale"

b) Italians Papers

7.4 ASR "As Built"

a) Final Documentation

b) "Relevant aspects in the design and construction of the ASR" P. Cavalleri, V. Bedogni, and A. Di Meglio 1984.

7.5 Pre-Acceptance Testing.

a) Testing report by AN

b) "ASR Incident on 7th September" A. Di Benedetti, A. Di Meglio - Italian Partners.

c) "Investigation Report Concerning ASR Incident 07.09.83" D. Stahl, D. Weyers - Interatom.

7.6 Evaluation Results.

a) "Preliminary results on the performance of the Sulzer cavity receiver and the Franco Tosi external receiver." C.S. Selvage and H. Jacobs 1984.

b) Internal Report on the latest preheating and filling procedure tested on 18.04.84 by the POA.

SSPS SEMIANNUAL REPORTS

SR 1	DCS Construction Report (by A. Kalt, M. Loosme, H. Dehne)	December 1982
SR 2	CRS Construction Report (by M. Becker, H. Ellgering, D. Stahl)	March 1983
SR 3	SSPS-DCS First Year of Operation (by A. Kalt)	July 1983
SR 4	SSPS-CRS First Period of Operation (by W. Bucher)	May 1984
SR 5	ASR Construction Experience Report	September 1984