



TerraThermal®

Reservoir Engineering

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INTRODUCTION

Successful exploitation of geothermal resources can be divided into three distinct stages (exploration, development, and production), and it is inherently an interdisciplinary effort:

- É Geochemistry
- É Geology
- É Geophysics
- É Reservoir engineering
- É Drilling
- É Construction
- É And others

High quality results are best obtained through teamwork.



ROLE OF THE RESERVOIR ENGINEER

Geoscientists and reservoir engineers work together to bring geothermal resources from exploration through development and into production:

É Exploration: typically, the geoscientists lead the effort, with the assistance of the reservoir engineers.

É Development: the geoscientists and reservoir engineers work together with contractors.

É Production: the reservoir engineers lead the effort, with the assistance of the geoscientists.

Other specialist contractors, such as landmen, permitters, drillers, EPC providers, etc. provide assistance as needed.



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EXPLORATION TASKS

Geoscientists

Field mapping
Reconnaissance
Remote sensing
Photogeology
Stratigraphy
Paleontology
Petrology
Geochronology
Geochemistry
Geophysics

Reservoir engineers

Analyze geochemistry data
Analyze geology data
Analyze geophysics data
Initial conceptual model
Natural state model
Assess reserves
Reservoir performance forecast
Injection/re-injection strategy



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DEVELOPMENT TASKS

Geoscientists

Well logging
Analyze cuttings
Analyze cores
Structural geology
Stratigraphy
Petrology
Hydrology
Tectonics
Refine field mapping
Engineering geology
Geological hazards
Soil mechanics

Reservoir engineers

Analyze well logs
Analyze cutting logs
Analyze core logs
Execute well testing plan
Refine conceptual model
Refine natural state model
Refine reserves
Refine performance forecast
Injection/re-injection strategy
Refine sustainable capacity



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PRODUCTION TASKS

Geoscientists

Periodic geochemistry

Monitor gravity

Monitor seismicity

Monitor subsidence

Refine field mapping

Reservoir engineers

Monitor reservoir performance

Periodic well testing plan

Refine conceptual model

Refine natural state model

Production history model

Refine reserves

Refine performance forecast

Injection/re-injection strategy

Refine sustainable capacity

Boost and maintain output



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AN EXAMPLE

A target of geothermal exploration is identified and explored. A single-well geothermal power system that might be developed to exploit this resource is conceptually designed. Such a system typically consists of the following components:

É Reservoir

É Well

É Separator

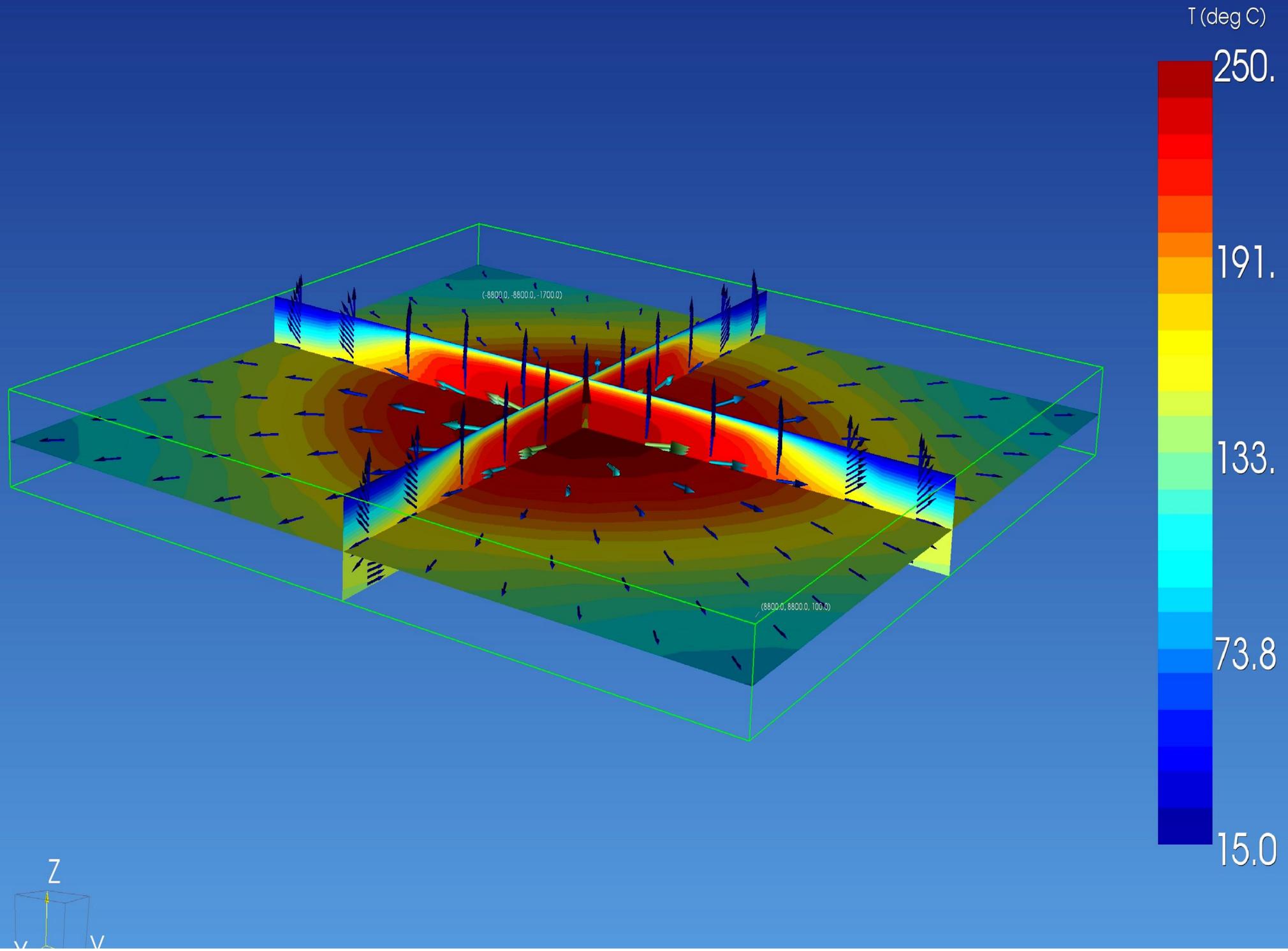
É Pipeline

É Turbine

É Condenser

É Generator

É Parasitics





THE RESERVOIR

When the target of geothermal exploration is identified and explored, and after a thorough exploration process, the following reservoir conditions are estimated:

Reservoir area:	$1.63 \times 10^8 \text{ m}^2$
Reservoir depth:	800 m
Reservoir thickness:	800 m
Reservoir temperature:	200°C



THE RESERVOIR

Based on the reservoir's estimated conditions and the estimated life of the surface equipment, a stored heat assessment is applied with the following results:

ÉTotal stored heat:	$6.74 \times 10^{19} \text{ J}$
ÉUsable stored heat:	$1.69 \times 10^{19} \text{ J}$
ÉNatural heat discharge:	350 MW_t
ÉNatural mass discharge:	300 kg/s
ÉMinimum power potential:	59 MW_e
ÉOptimum power potential:	778 MW_e



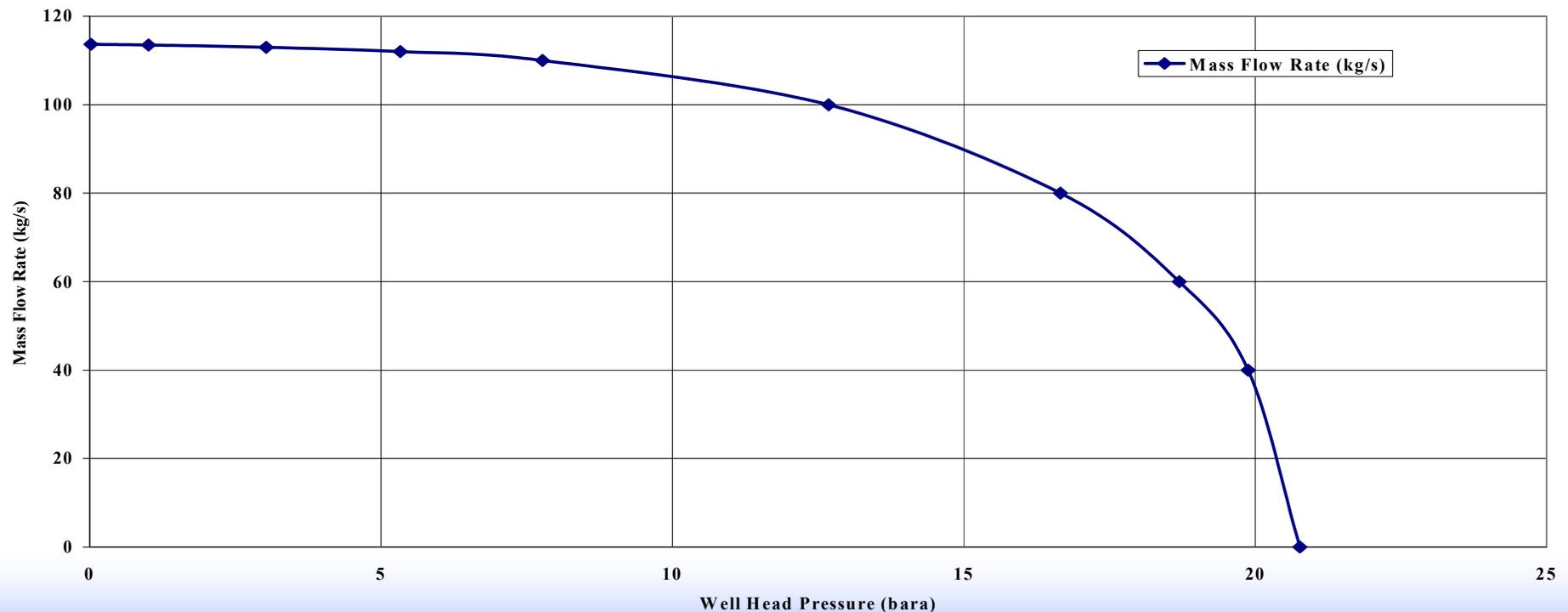


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THE WELL

Based on the reservoir conditions and using a well-bore flow simulator, a flow model of the well is constructed, and it has the following characteristics:

Output Curve



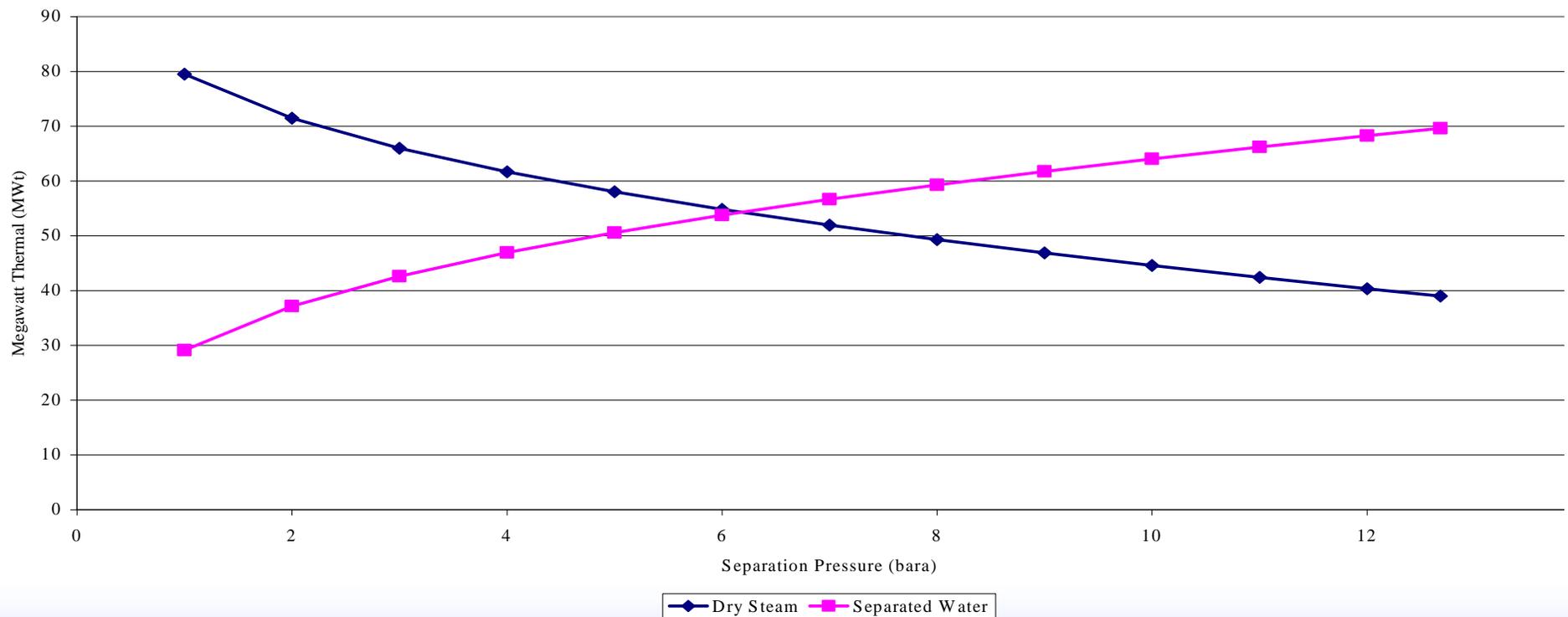




THE SEPARATOR

Based on the flowing well head conditions, a model of the separator is constructed, and it has the following characteristics:

Separator



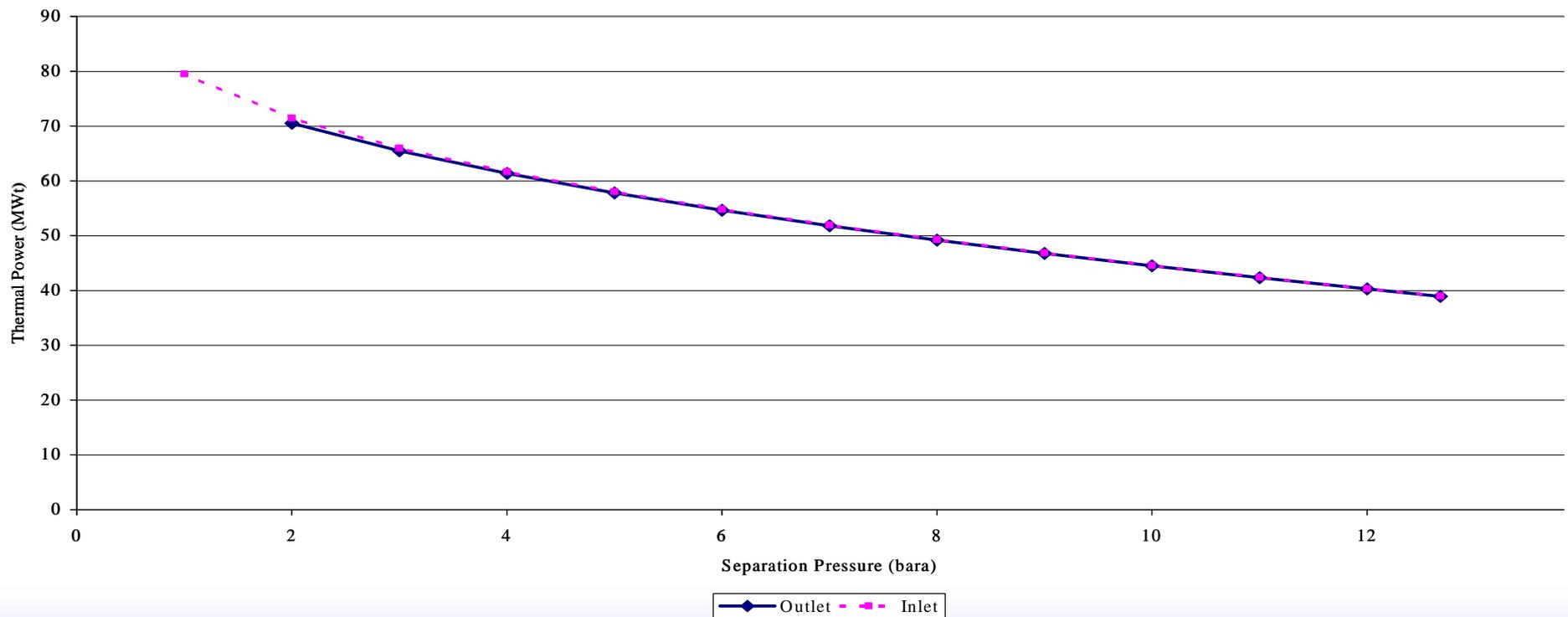




THE PIPELINE

Based on the separator outlet conditions, a model of the steam pipeline is constructed, and it has the following characteristics:

Pipeline





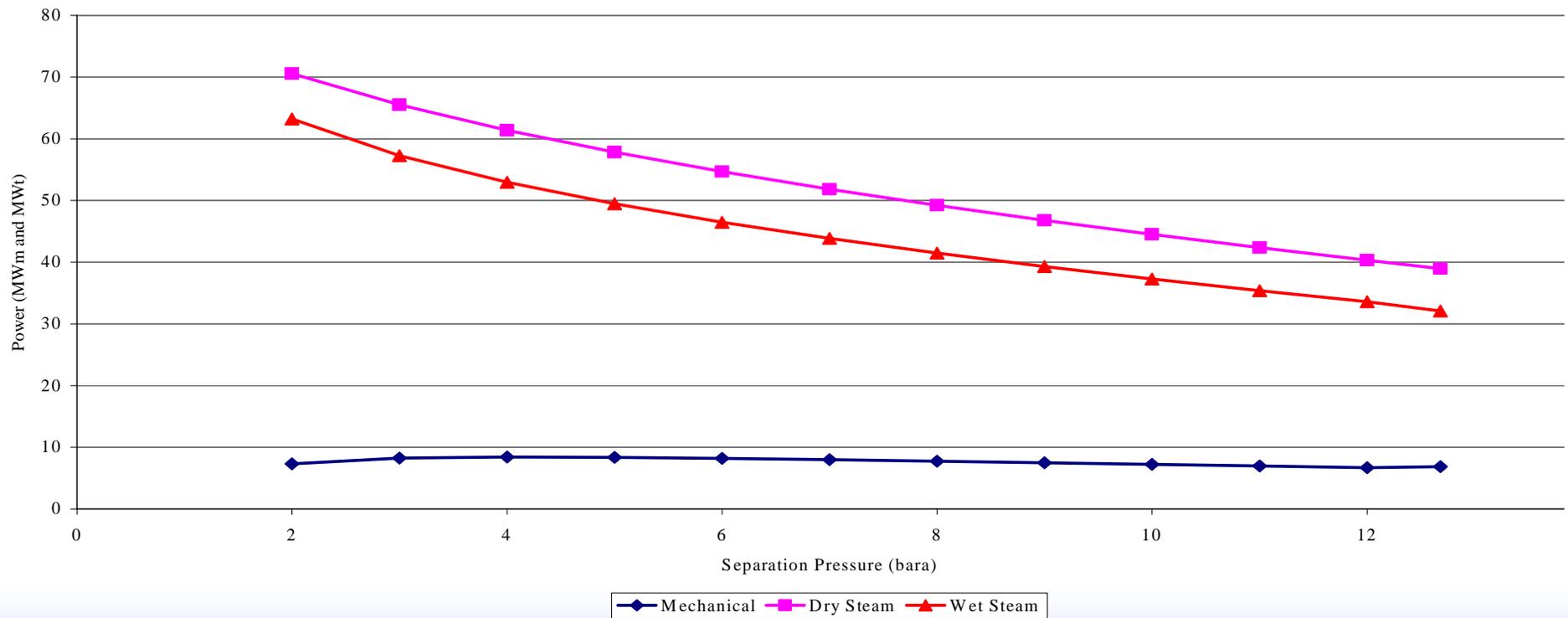
Courtesy of Sadiq J. Zarrouk, Ph.D.,
Geothermal Institute



THE TURBINE

Based on the pipeline outlet conditions, a model of the steam turbine is constructed, and it has the following characteristics:

Turbine





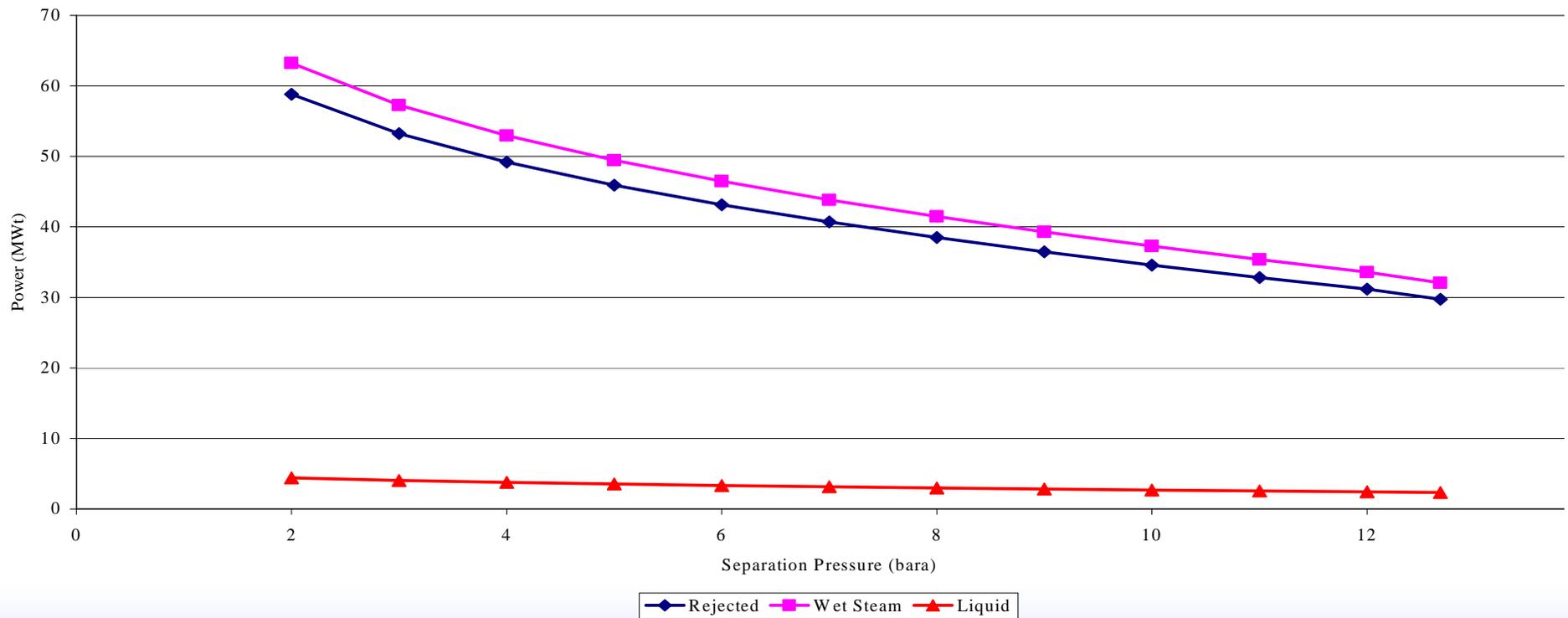
Courtesy of Sadiq J. Zarrouk, Ph.D.,
Geothermal Institute



THE CONDENSER

Based on the turbine outlet conditions, a model of the condenser is constructed, and it has the following characteristics:

Condenser



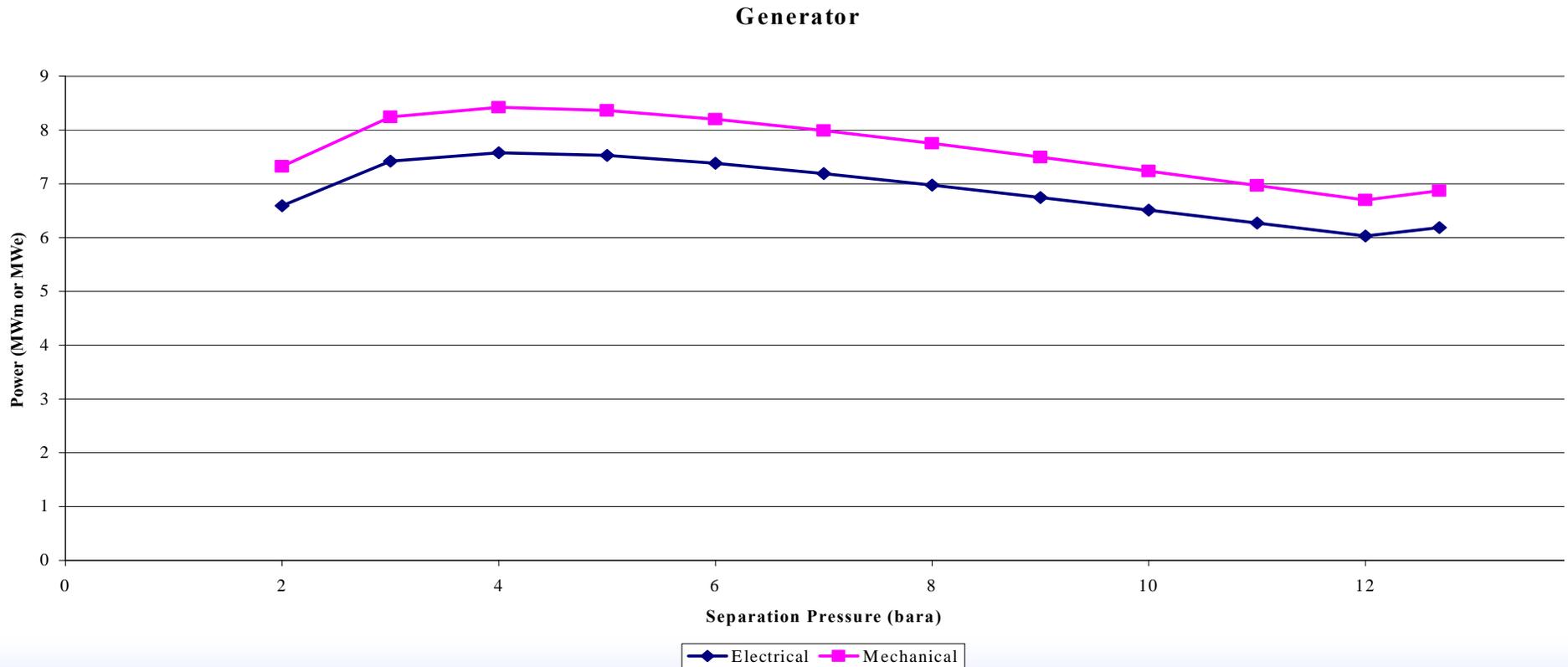


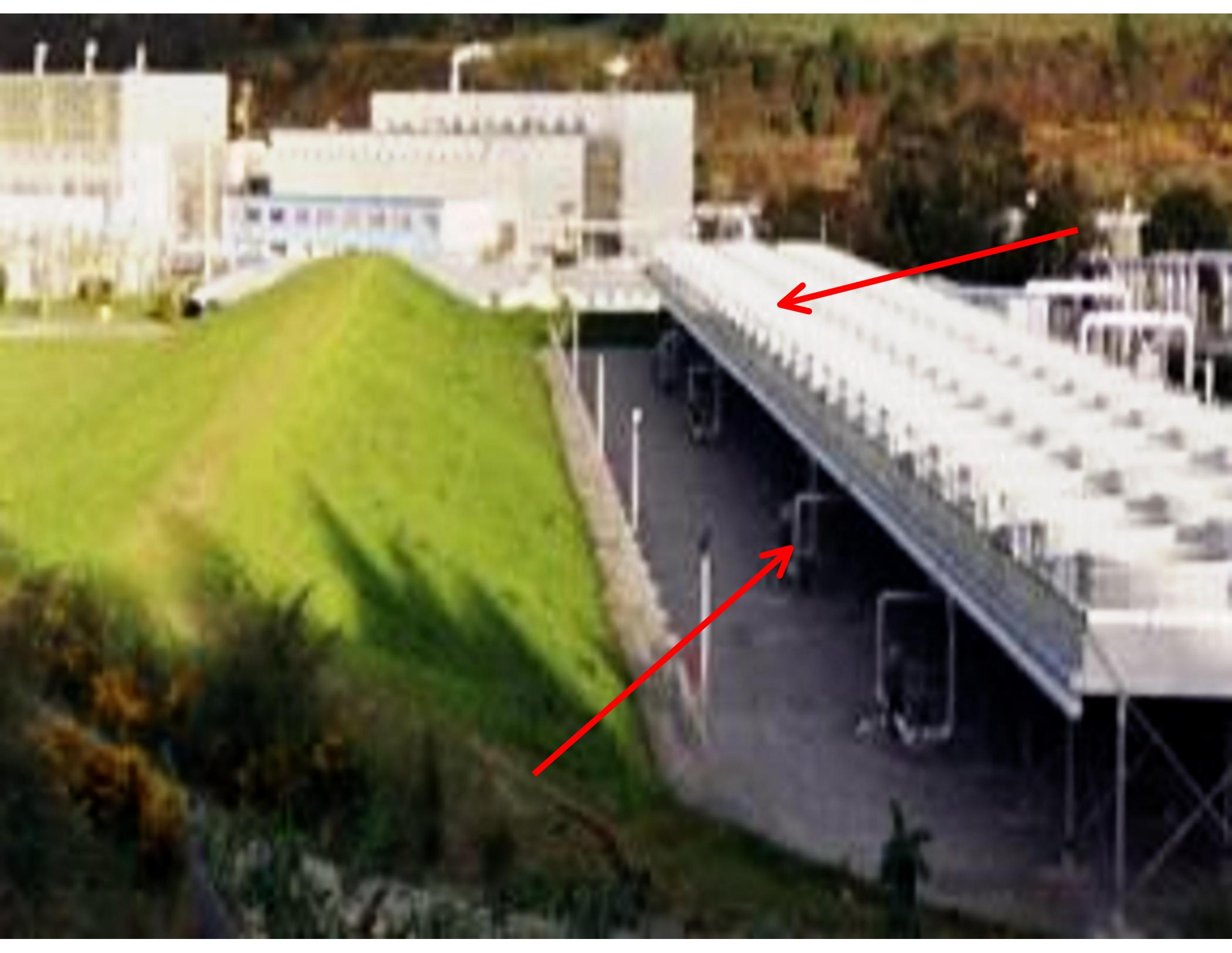
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Geothermal Institute



THE GENERATOR

Based on the turbine outlet conditions, a model of the generator is constructed, and it has the following characteristics:



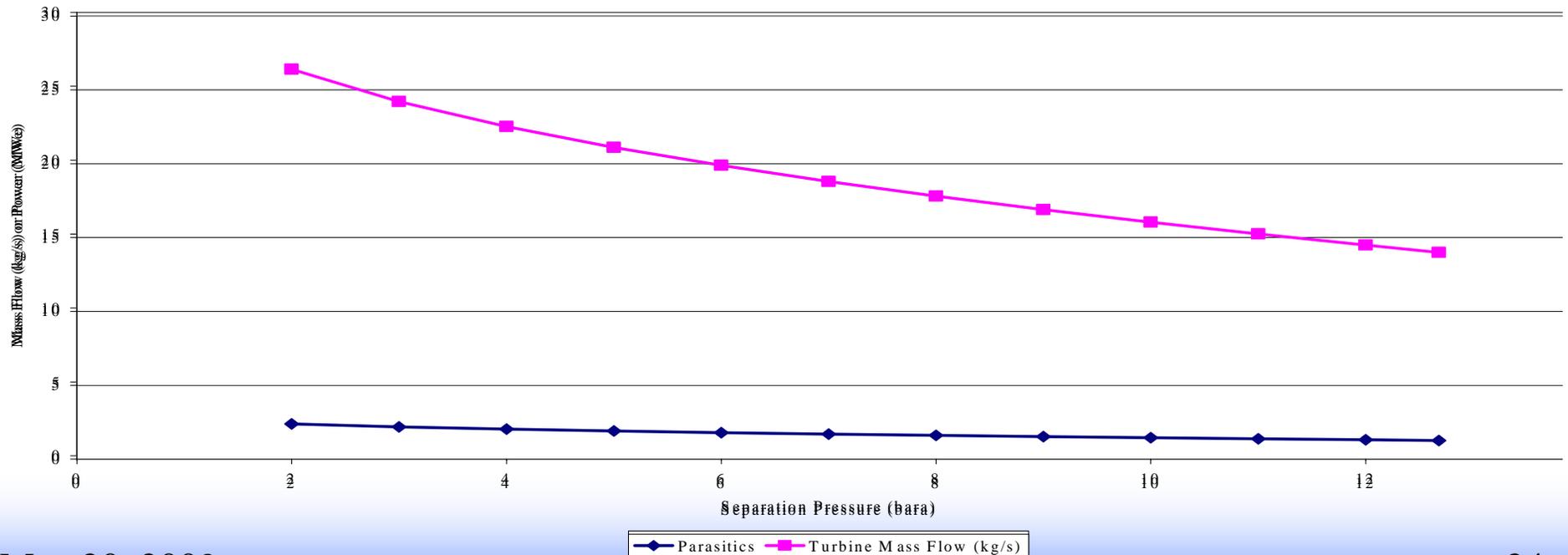




THE PARASITICS

Based on the generator inlet and outlet conditions and the power required to run fans, fluid pumps, gas ejectors, etc. a model of the power plant parasitic power consumption is constructed, and it has the following characteristics:

Parasitics



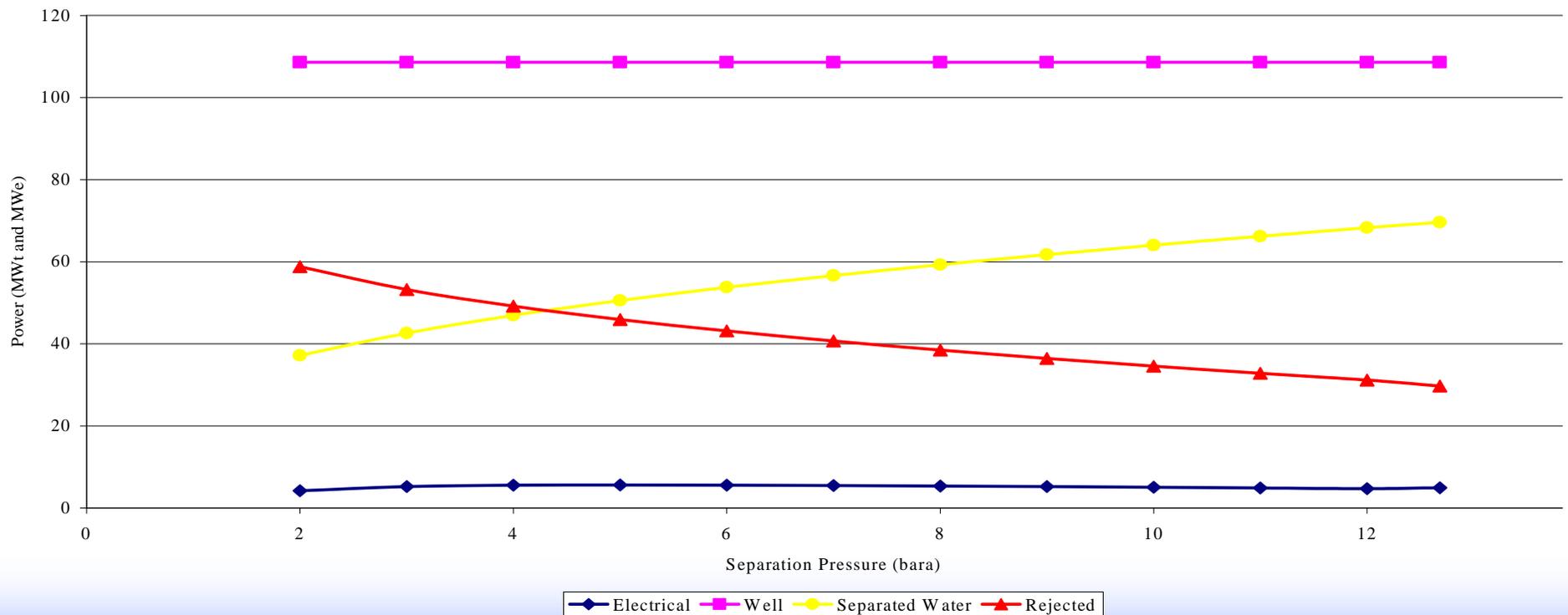




THE SYSTEM

Based on the reservoir conditions, a model of the proposed power system is constructed, and it has the following characteristics:

System





THE ECONOMICS

A cost and output model of the power plant is constructed, and it has the following characteristics:

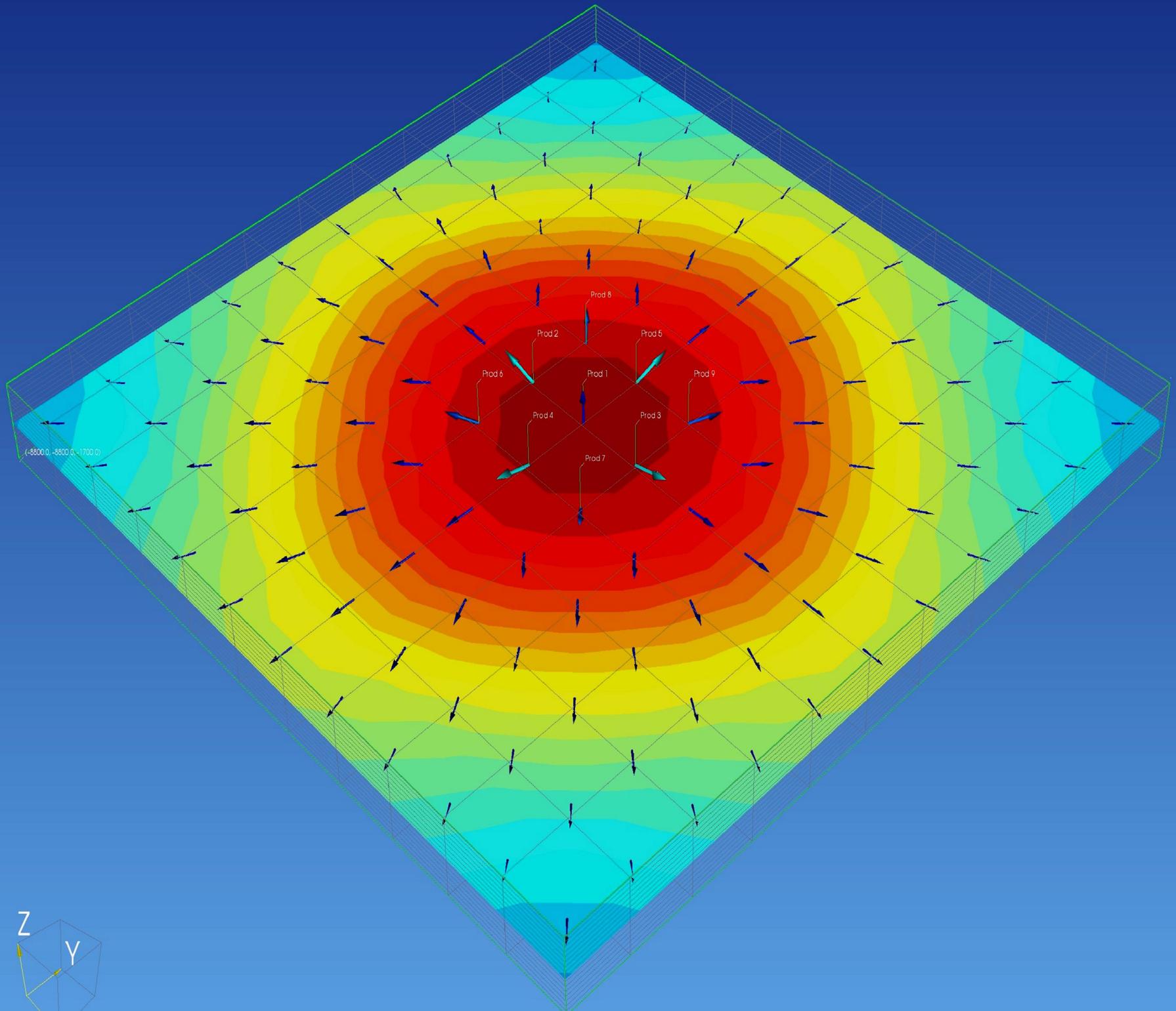
Exploration costs	\$ 100,000
Confirmation drilling costs	\$ 1,000,000
Development costs	\$21,300,000
Power production:	46,635 MWh / year
Production costs (O & M):	\$ 394,970 / year
Power sales (\$50/MWh):	\$2,331,750 / year
REC sales (\$50/REC):	\$2,331,750 / year



THE ECONOMICS

Based on the cost and output model of the power plant is , we can estimate the power generation cost for various interest rates:

CAPITAL COST (\$)	\$22,400,000	\$22,400,000	\$22,400,000
INTEREST RATE (%)	6.00	8.00	10.00
POWER SYSTEM LIFE (YEARS)	30	30	30
ANNUALIZED CAPITAL COST (\$/YEAR)	\$746,667	\$746,667	\$746,667
ANNUALIZED INTEREST COST (\$/YEAR)	\$880,669	\$1,243,068	\$1,629,508
POWER SYSTEM CAPACITY (MWe)	5.60	5.60	5.60
POWER SYSTEM CAPACITY FACTOR	0.95	0.95	0.95
TOTAL ANNUAL GENERATION (MWh/YEAR)	46635.12	46635.12	46635.12
CAPITAL COST (\$/MWh)	16.01	16.01	16.01
INTEREST COST (\$/MWh)	18.88	26.66	34.94
O & M COST (\$/MWh)	\$15.00	\$15.00	\$15.00
TOTAL GENERATION COST (\$/MWh)	\$49.90	\$57.67	\$65.95



T (deg C)

250.

191.

133.

73.8

15.0

$(-8800, 0, -8800, 0, -17000, 0)$



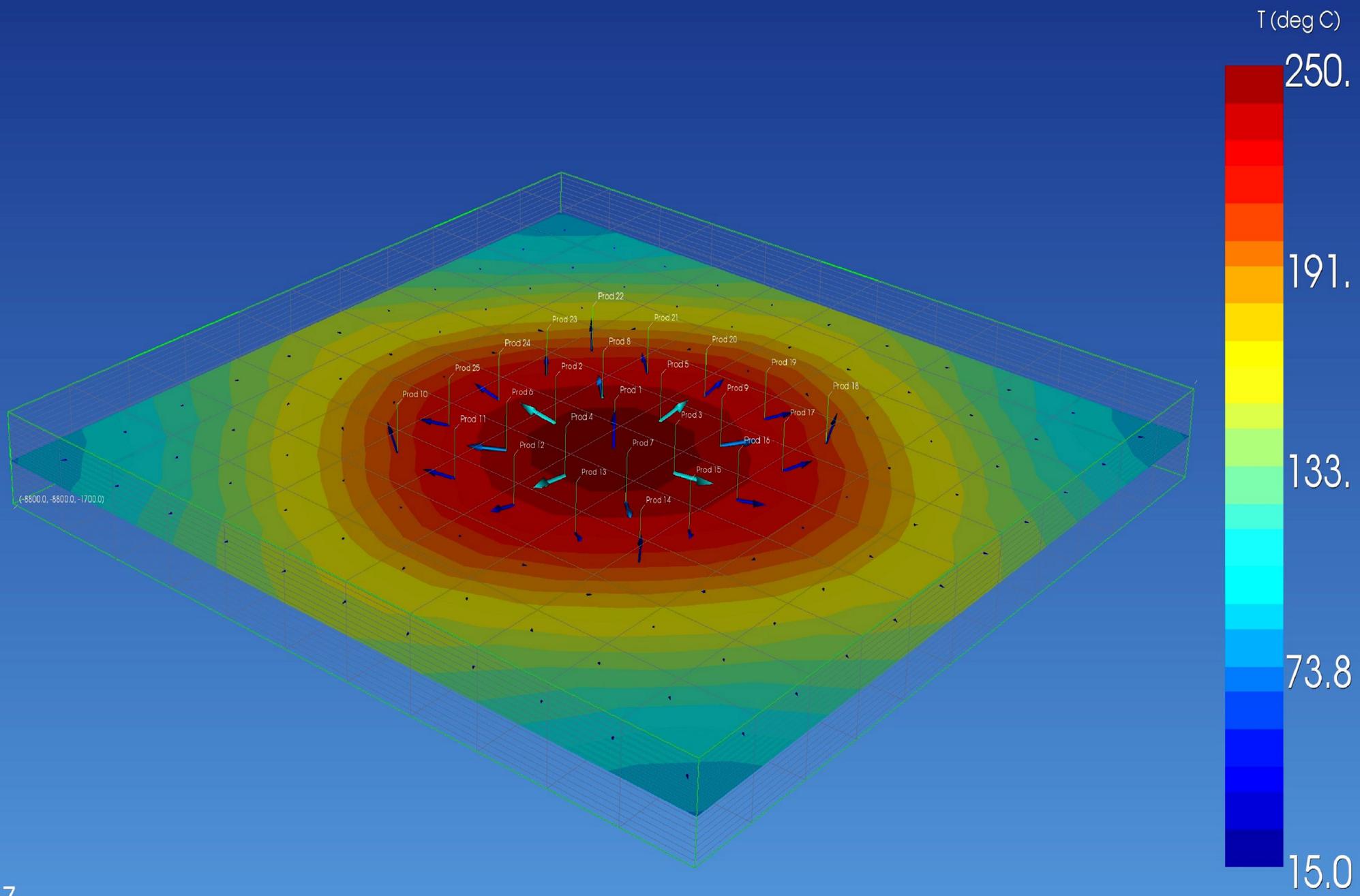


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BUILD-OUT, PHASE I

A decision was made to build out the production field from 1 well to 9; the system now has the following characteristics:

Exploration costs	\$ 100,000
Confirmation drilling costs	\$ 1,000,000
Development costs	\$200,500,000
Power production:	419,715 MWh / year
Production costs (O & M):	\$ 62,957,725 / year
Power sales (\$50/MWh):	\$20,985,750 / year
REC sales (\$50/REC):	\$20,985,750 / year





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BUILD-OUT, PHASE II

A decision was made to build out the production field from 9 wells to 25; the system now has the following characteristics:

Exploration costs	\$ 100,000
Confirmation drilling costs	\$ 1,000,000
Development costs	\$558,900,000
Power production:	1,165,875 MWh / yr
Production costs (O & M):	\$17,488,125 / year
Power sales (\$50/MWh):	\$58,293,750 / year
REC sales (\$50/REC):	\$58,293,750 / year



WHY GEOTHERMAL ?

Parameter	Oil	Gas	Coal	Solar	Wind	Hydro	Geo
Affordable	2	3	7	1	4	5	6
Clean	2	3	1	6	5	4	7
Domestic	1	2	3	4	5	6	7
Plentiful	1	2	3	7	6	4	5
Reliable	4	5	6	1	2	3	7
Secure	1	2	3	4	5	6	7
Total	11	17	24	23	27	28	39



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QUESTIONS ?

