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CLASSIFICATION OF GEOTHERMAL SYSTEMS – A POSSIBLE SCHEME

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ABSTRACT

At the request of the United States Department of Energy, the author was asked by the Geothermal Energy Association (Washington, D.C.) to prepare a white paper on the subject (in connection with a new national assessment of geothermal resources). This paper offers a possible scheme in which geothermal resources are classified into seven categories based on temperature: non-electrical grade (<100°C), very-low temperature (100°C to <150°C), low temperature (150°C to 190°C), moderate temperature (190°C to <230°C), high temperature (230°C to <300°C), ultra-high temperature (>300°C), and steam fields (approximately 240°C with steam as the only mobile phase). In the first four classes of reservoirs, liquid water is the mobile phase; in the "high" and "ultra-high" temperature reservoirs, the mobile fluid phase is either liquid or a liquid-vapor mixture.

This scheme is based not only on temperature but also according to a set of additional attributes important for practical utilization of geothermal energy: (a) steam fraction in the mobile fluid phase in the reservoir (a controlling factor in reservoir performance), (b) type of power generation technology applicable, (c) production mechanism and the state of the fluid at the wellhead (which influence operational economics), (d) factors other than temperature that control well productivity (these factors affect the optimization of field development and operation), and (e) unusual operational problems that impact power cost (such as scaling, corrosion, high content of non-condensable gases, etc.). The paper discusses the rationale for this scheme and why some other possible schemes were not considered. Finally, the paper considers the distribution of the identified geothermal systems in the United States *vis a vis* these categories. The author invites comments on this scheme that may lead to a generally accepted one.

INTRODUCTION

In June 2004, the United States Department of Energy (DOE) approached the Geothermal Energy Association (GEA), a U.S. trade organization based in Washington (D.C.), to propose an approach to classification of geothermal systems. The need for such a classification scheme stems from the proposed national assessment of the geothermal resources in the United States. Based on a discussion between the DOE and GEA, the author was asked by the GEA to prepare a white paper that could serve as a basis for arriving at a formal classification scheme; this paper is the product.

A BASIS FOR CLASSIFICATION

Many possible criteria for such classification are available, but most would agree that for classifying geothermal resources, reservoir temperature should be the primary criterion. Table 1 offers 7 possible classes based on temperature as the primary criterion and steam fraction in the mobile fluid phase in the reservoir (but not necessarily steam saturation in the reservoir) as a secondary criterion. The reservoir temperature limits suggested in Table 1 can be shifted by 5° to 10°C without disrupting the logical structure of the scheme, which is summarized below. The scheme is illustrated on a pressure-enthalpy-temperature diagram for pure water on Figure 1. The attributes of the reservoirs in the various classes, as depicted in Figure 1 and listed in Table 1, reflect general industry experience.

Class 1 (less than 100°C): The boiling point of water at atmospheric pressure, 100°C, is a reasonable lower limit for power generation from a geothermal fluid; no commercial geothermal power project has been developed based on a resource cooler than 100°C. Therefore, a resource in this class is suitable only for non-electrical uses.

Class 2 (100°C to less than 150°C): The mobile fluid phase in these reservoirs is liquid water. Only three power projects (totaling about 6 MWe capacity) have been developed in the U.S. based on geothermal resources in the 100° to 150°C temperature range, and these projects have proven only marginally commercial. Well productivity for such a resource would be less than 5 MWe, the typical range being 2 to 4 MWe. Geothermal resources in this temperature range call for pumped wells and binary-cycle power generation. Given the significant advances made in downhole pump and binary-cycle power generation technologies over the last two decades, power generation from resources in this temperature range is eminently commercial today. The 150°C temperature limit is somewhat arbitrary and may be moved either way by perhaps up to 10°C.

<u>Class 3 (150°C to less than 190°C):</u> The mobile fluid phase in these reservoirs is liquid water. A number of commercial power projects have been operated over the last two decades using geothermal resources in the 150° to 190°C range, the latter temperature being the limit of operation of commercially available downhole pumps today; geothermal water over most of this temperature range must be pumped because the fluid does not have sufficient energy for self-flow at a commercial rate. However, at the upper end of this temperature range wells may be either pumped or self-flowed (if the reservoir flow capacity is relatively large). Well productivity for such a resource would be less than 7 MWe, the typical range being 3 to 6 MWe. While temperature tolerance for commercial pumps may some day exceed 190°C, the higher vapor pressure at higher temperatures might reduce the available pressure drawdown sufficiently to make pumping less attractive than self-flow. Therefore, the 190°C limit for this range is reasonably well defined.

<u>Class 4 (190°C to less than 230°C):</u> The next higher resource temperature limit is chosen as 230°C, which is lower than the minimum initial resource temperature encountered in vapor-dominated reservoirs worldwide. Vapor-dominated reservoirs have such a unique set of characteristics that these have been grouped as a separate class as described below. Reservoirs above a temperature level of 230°C may have free steam saturation initially or develop steam saturation upon exploitation, but this would be unlikely for a reservoir below a 230°C temperature level. Thus, reservoirs in the 190° to 230°C range should have liquid water as the mobile fluid phase, and as such, this class is reasonably well constrained. The wells for this class would be too hot to pump and must be self-flowed. Therefore, the productivity of wells in this class would be more variable, typically in the range of 3 to 12 MWe.

<u>Class 5 (230°C to less than 300°C):</u> Above a temperature level of 230°C, the reservoir would be expected to become two-phase at some point during exploitation. The next higher temperature limit of 300°C is rather arbitrary; changing it by perhaps up to 20°C will not affect the classification. For this class of resource, as well as for classes 6 and 7, well productivity varies within an extremely wide range, depending on reservoir flow capacity as well as the extent of steam saturation in the reservoir, which, together with the relative permeability characteristics of the reservoir, determines the steam fraction in the mobile fluid phase. Individual well productivities as high as 50 MWe have been reported for fields in classes 5 through 7.

<u>Class 6 (greater than 300°C):</u> Such reservoirs are characterized by rapid development of steam saturation in the reservoir and steam fraction in the mobile fluid phase upon exploitation. The performance of such reservoirs, specifically the evolution of production enthalpy, is generally difficult to forecast with any confidence. The upper temperature limit for this class may be considered the critical temperature of water (374.1°C). A temperature significantly higher than the critical is unlikely to be encountered in a productive well for a number of physical reasons.

<u>Class 7 (Steam fields):</u> This special class of resource needs to be recognized, its uniqueness being the remarkably consistent initial temperature and pressure (approximately 240°C and 33.5 bar-a) displayed by all such fields in the world: Kamojang (Indonesia), The Geysers (California), Lardanello (Italy), Matsukawa (Japan), Darajat (Indonesia), etc. Furthermore, the enthalpy of the resource in such a field is the maximum enthalpy possible for saturated steam (2,800 kJ/kg). Since a pervasively superheated steam reservoir is physically unlikely (notwithstanding occasional cases of superheated steam production at the wellhead), a Class 7 resource typically has the largest available energy per unit mass of all classes. Therefore, wells of 30 to 50 MWe capacity are not uncommon in such fields.

Ignoring geothermal resources in the National Parks, The Geysers is the only such field in the U.S. Given the pivotal importance of The Geysers to the U.S. geothermal industry, this class is recognized separately. It should be noted that the low-pressure steam reservoir exploited until recently at Cove Fort (Utah) is unique and such low-pressure steam reservoirs are generally “steam caps” over a liquid reservoir and do not represent a significant commercial resource. Incidentally, the plant at Cove Fort has been shut down and a new plant is planned to be operated using water occurring below the steam cap.

IS THE PROPOSED CLASSIFICATION REASONABLE?

A useful classification should be one that can ascribe a consistent set of practically useful attributes to each class; Table 1 lists these for the proposed scheme. From the viewpoint of power plant development and operation, the important attributes are the following: (a) steam fraction in the mobile fluid phase in the reservoir (a controlling factor in reservoir performance), (b) type of power generation technology applicable, (c) production mechanism and the state of the fluid at the wellhead (which influence operational economics), (d) factors other than temperature that control well productivity (these factors affect the optimization of field development and operation), and (e) unusual operational problems that impact power cost (such as scaling, corrosion, high content of non-condensable gases, etc.).

As seen from Table 1, the proposed classification manages to pigeon-hole geothermal resources not only according to temperature (which uniquely determines, except for Class 7, the available MWe per unit mass production rate) but also according to the above set of additional attributes. Furthermore, this classification scheme leads to consistently increasing MWe reserves per identified field in the U.S. (Figure 2) as one considers progressively higher classes. Figure 2 is based on data shown in Table 2, which in turn draws upon the results of the last nationwide assessment of geothermal resources conducted by the U.S. Geological Survey in 1978 (Muffler, 1979). It is clear from Table 2 and Figure 2 that the number of identified fields declines but the MWe reserves per field increase, nearly exponentially in both cases, as one considers progressively higher temperature classes, the steam field category (Class 7) being, of course, an exception.

While progressively higher temperature classes are expected to show higher levels of power potential per unit mass production rate, the curious empirical fact of progressively higher reserves per field for higher temperature classes adds another dimension to the conceptual consistency of the proposed classification. As such, the scheme appears reasonable.

COULD WE CHOOSE SOME OTHER BASIS FOR CLASSIFICATION?

We could, but the above-described consistency would be lost. For example, one could consider geology as the main classification criterion. While it might be an interesting intellectual exercise, there is no consistent set of practically useful attributes that would characterize a geologic environment (volcanic, sedimentary, metamorphic, etc), or a geologic province (Basin and Range, Imperial Valley, etc in the U.S.). For example, within the Imperial Valley, Salton Sea is a far larger, hotter and more saline field than either East Mesa or Heber. Within the same Basin and Range province, the Dixie Valley field has entirely different reservoir characteristics than does Steamboat, and so on.

Similarly, consideration of reservoir depth or permeability (or any other petrophysical property, for that matter) as a classification criterion does not lead to satisfactory pigeon-holing of the above-mentioned attributes. For example, there are numerous wells in Nevada and the adjoining region of California that consistently produce 3 to 4 MWe from a remarkably wide depth range (less than 150 m to greater than 2,500 m); and the permeability-thickness values of the exploited fields range from less than 300 to more than 300,000 millidarcy-meter without serving as a unique or ready indicator of commercial prospects of the fields. As regards depth, for example, The Geysers reservoir has seen commercial production from a depth range of 300 to 4,000 m. Then, to which class, in a depth-based classification, should The Geysers belong? Similarly, within the same reservoir, petrophysical properties can easily vary by orders of magnitude. How could one then pigeon-hole such a reservoir with a classification scheme based on a petrophysical property? In addition, the range of production depths or petrophysical properties of a field can only be defined after a significant amount of development drilling. Reservoir temperature, on the other hand, can be approximated from geochemical exploration and heat flow studies long before a field is confirmed by drilling or considered for commercial development. This is one more advantage of a temperature-based classification.

The choice of a basis for classification ultimately hinges on the purpose of such a classification. In this paper, we have assumed the purpose to be standardization of references to various geothermal systems (in a national inventory) as regards their commercial prospects; this is apparently what the wind industry has done. As such, this paper has disregarded the possibility of alternative schemes of classification based on criteria less relevant to the commercial world.

HOW CAN ENHANCED GEOTHERMAL RESOURCES BE CLASSIFIED?

There is no readily apparent logical basis to classify enhanced geothermal systems (EGS) or hot dry rock (HDR) resources other than perhaps considering temperature-based classes as discussed above; unfortunately, as shown below, even classification according to temperature may not be particularly meaningful. One can superimpose on such temperature classes some consideration of the *in-situ* stress regime to define sub-classes; but given the paucity of data on underground stress regimes this approach may prove illusory. Another possible approach could be to define two broad groups of EGS projects, those developed in purely conductive systems and those developed in tight parts of convective systems (Sanyal and Butler, 2004); EGS field demonstration projects, supported by the U.S. Department of Energy, at Coso and Desert Peak fall in the latter group, while the Fenton Hill (New Mexico) experiment conducted in the 1970s and

1980s involved the former. For either group, further classification based on temperature is an option; even the stress regime might be invoked for defining yet further subclasses.

Temperature is an unsatisfactory criterion for classifying EGS projects, because unlike a hydrothermal system, the characteristics of an EGS reservoir are largely engineered. Therefore, some of the attributes listed in Table 1 for the various temperature classes would not prove meaningful. For example, productivity of a well will depend more on the extent of artificial enhancement of reservoir flow capacity than on the intrinsic porosity or permeability or even temperature of the formation. For any specific temperature range, most of these attributes (applicable power generation technology, production mechanism, fluid state at the wellhead, etc.) are not expected to be unique but will depend also on the nature and extent of artificial enhancement of permeability and the injection/production configuration employed (doublet, triplet, 5-spot, etc.) and its dimensions. Therefore, the extent of permeability enhancement or injection/production scheme employed is as important a criterion for classification as is temperature.

Given the limited practical experience with EGS projects to date and the above-discussed conceptual limitations, it is too early to attempt to develop a classification scheme for EGS projects. Perhaps such a classification scheme should be considered after significant results from EGS experiments and field developments, at Coso and Desert Peak as well as in Australia and Europe, become available. In any case, the absence of a classification scheme should not hold up progress on the EGS front for the foreseeable future.

REFERENCE

Muffler, L. J. P., Editor, 1979. “Assessment of Geothermal Resources of the United States – 1978,” Geological Survey Circular 790, United States Department of the Interior, 1979.

Sanyal, Subir K. and Steven J. Butler (2004), “National Assessment of U.S. Enhanced Geothermal Resources Base – A Perspective,” Trans., Geothermal Resources Council, Palm Springs, California, Volume 28, August – September, 2004, pp 233-238.

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Table 1. A Possible Classification Scheme for Geothermal Resources

Class of Resource	**Reservoir Temperature**	**Mobile Fluid Phase in Reservoir**	**Production Mechanism**	**Fluid State at Wellhead**	**Well Productivity and Controlling Factors other than Temperature**	**Applicable Power Conversion Technology**	**Unusual Development or Operational Problems**
1. Non-electrical Grade	< 100°C	Liquid water	Artesian self-flowing wells; pumped wells	Liquid water	Well productivity dependent on reservoir flow capacity and static water level	Direct Use	
2. Very Low Temperature	100°C to < 150°C	Liquid water	Pumped wells	Liquid water (for pumped wells); steam-water mixture (for self-flowing wells)	Typical well capacity 2 to 4 MWe; dependent on reservoir flow capacity and gas content in water; well productivity often limited by pump capacity	Binary	
3. Low Temperature	150°C to < 190°C	Liquid water	Pumped wells; self-flowing wells (only at the higher-temperature end of the range)	Liquid water (for pumped wells); steam-water mixture (for self-flowing wells)	Typical well capacity 3 to 5 MWe; dependent on reservoir pressures, reservoir flow capacity and gas content in water; productivity of pumped wells typically limited by pump capacity and pump parasitic power need; productivity of self-flowing wells strongly dependent on reservoir flow capacity	Binary; Two-stage Flash; Hybrid	Calcite scaling in production wells and stibnite scaling in binary plant are occasional problems
4. Moderate-Temperature	190° to < 230°C	Liquid water	Self-flowing wells	Steam-water mixture (enthalpy equal to that of saturated liquid at reservoir temperature)	Well productivity highly variable (3 to 12 MWe); strongly dependent on reservoir flow capacity	Single-stage Flash; Two-stage Flash; Hybrid	Calcite scaling in production wells occasional problem; alumino-silicate scale in injection system a rare problem

Table 1. A Possible Classification Scheme for Geothermal Resources

Class of Resource	**Reservoir Temperature**	**Mobile Fluid Phase in Reservoir**	**Production Mechanism**	**Fluid State at Wellhead**	**Well Productivity and Controlling Factors other than Temperature**	**Applicable Power Conversion Technology**	**Unusual Development or Operational Problems**
5. High Temperature	230°C to < 300°C	Liquid water; Liquid-dominated two-phase	Self-flowing wells	Steam-water mixture (enthalpy equal to or higher than that of saturated liquid at reservoir temperature); saturated steam	Well productivity highly variable (up to 25 MWe); dependent on reservoir flow capacity and steam saturation	Single-stage Flash; Hybrid	Silica scaling in injection system; occasionally corrosion; occasionally high NCG content
6. Ultra High Temperature	300°C+	Liquid-dominated two-phase	Self-flowing wells	Steam-water mixture (enthalpy equal to or higher than that of saturated liquid at reservoir condition); saturated steam; superheated steam	Well productivity extremely variable (up to 50 MWe); dependent on reservoir flow capacity and steam saturation	Single-stage Flash	High NCG content; silica scaling in injection system; occasionally corrosion; silica scaling potential in production wells at lower wellhead pressures
7. Steam Field	240°C (33.5 bar-a pressure; 2,800 kJ/kg enthalpy)	Steam	Self-flowing wells	Saturated or superheated steam	Well productivity extremely variable (up to 50 MWe); dependent on reservoir flow capacity	Direct steam	Occasionally high NCG content or corrosion

Table 2. Distribution of Identified Hydrothermal Systems in the U.S. among the Resource Classes*

Resource Class	**Reservoir Temperature**	**No. of Identified Systems**	**Reserves in Identified Systems**
2. Very Low Temperature	100°C to < 150°C	134	8,000 MWe
3. Low Temperature	150°C to < 190°C	34	5,500 MWe
4. Moderate Temperature	190° to < 230°C	11	4,300 MWe
5. High Temperature	230°C to < 300°C	7	8,200 MWe
6. Ultra High Temperature	300°C+	1	2,000 MWe
7. Steam Field	230°C to 240°C	1	1,000 MWe
	Total:	188	29,000 MWe

* Excluding systems in National Parks

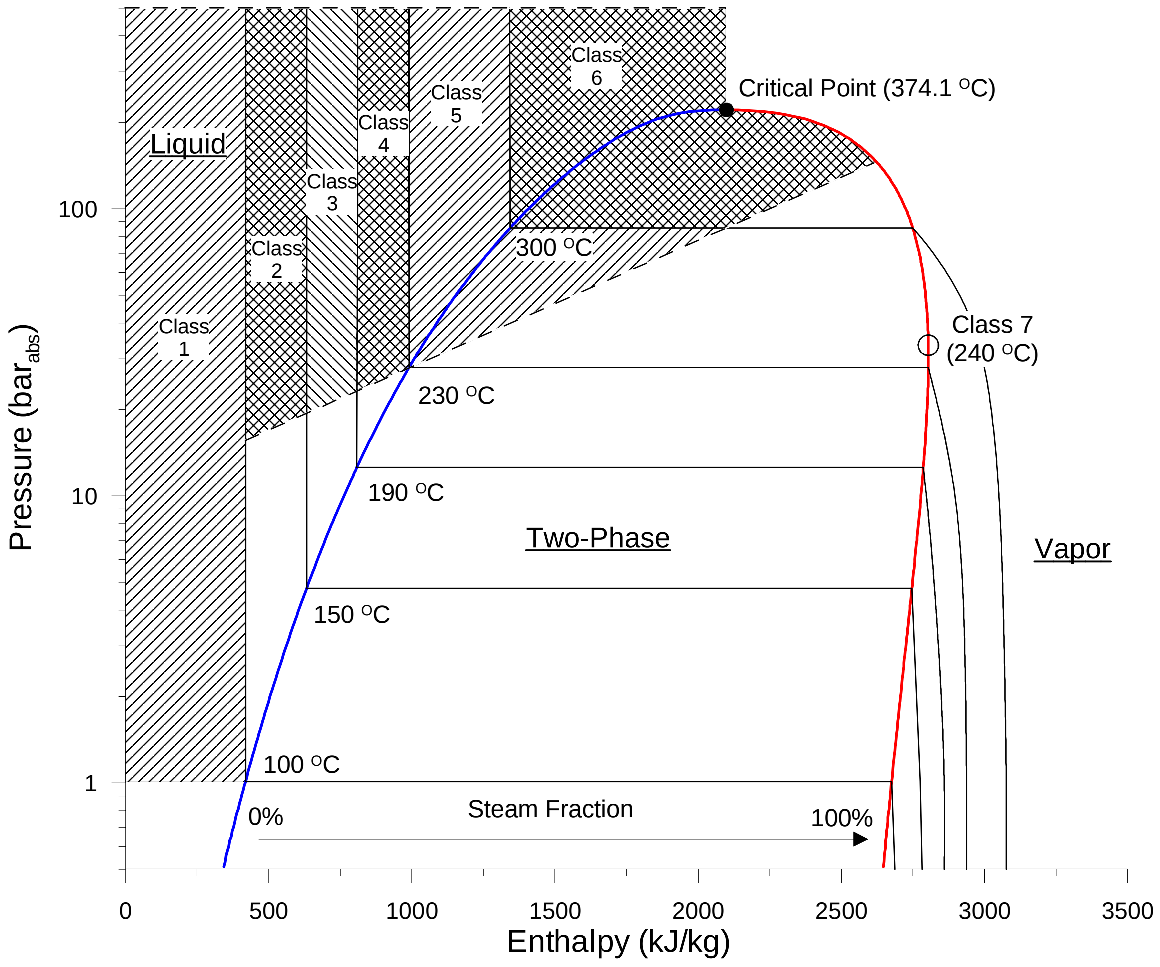

Figure 1: Classification Scheme on Pressure-Enthalpy-Temperature Diagram for Water.

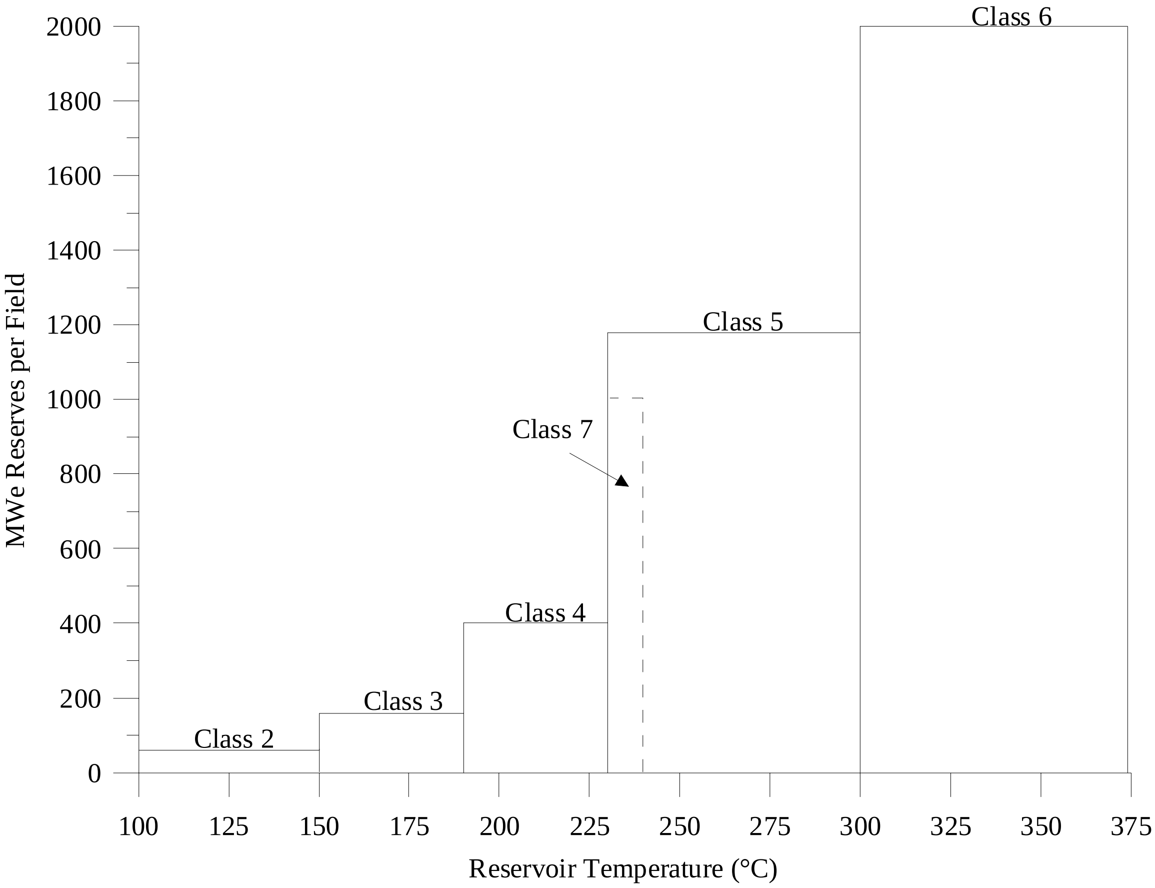

Figure 2. MWe Reserves per Identified Field for Various Resource Classes